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OPTICAL QUALITY OF TILTED SPHERICAL MIRROR UNSTABLE RESONATORS

U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND



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Redstone Arsenal, Alabama 35809

R. William Jones, James C. Nixon, and Charles Cason High Energy Laser Laboratory

and

James F. Perkins
University of Alabama



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A new class of resonators has recently been perty of having different magnifications M and M	
perpendicular to the propagation direction; the rethose with collimated output analagous to convent	cional confocal unstable reso
nators. The designs utilize spherical mirrors wh	nich are tilted substantially.
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from the mirror normal. The conventional orientation requires the mirror normal to be along (or very nearly parallel to) the propagation direction. Use of spherical mirrors by this new class of resonators eliminates the difficulties of fabricating mirrors with more complex figures, which would otherwise be required to achieve the desired asymmetric magnification. The critical problem of keeping beam-quality degradation (aberrations) due to mirror tilt within acceptable limits has been examined experimentally and analytically. The results confirm the possibility of achieving acceptable small aberrations for large tilt angles (convex mirror tilt as large as 70°, corresponding to 140° beam deflection) to operation at infrared wavelengths.

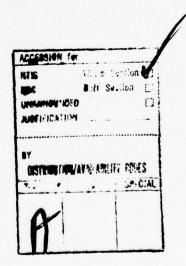
A confirmation of the tilted spherical mirror resonator concept was validated theoretically and experimentally by choosing a convex/concave mirror set with small radii of curvature (small f number). The deliberately exaggerated aberrations were compared by experimental interferometry and computational plots of optical path differences. The results of experiment and theory agreed quantitatively.

The following conclusions were drawn from this work:

- The sense of relative tilt of the spherical mirrors affects the aberrations.
- 2) The dominant terms contributing to aberrations are of the form y^3 and x^2y with y^3 predominating for high aspect ratio resonators.
- 3) The concept has many advantages over toroidal resonators used with linear chemical lasers. Chemical laser development programs experiment with varying values of $\mathbf{x}_{\mathbf{c}}$, thereby requiring several sets of toroidal mirrors for beam extraction. The present concept has the ability to vary $\mathbf{M}_{\mathbf{x}}$ continuously to account for planned variations in $\mathbf{x}_{\mathbf{c}}$ of interest in chemical laser development experiments, thereby requiring no more than one resonator.

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I. INTRODUCTION

This new class of resonators, which possesses certain unique and desirable features, was proposed and discussed earlier. The basic design equations were derived and experimentally confirmed, and a report was given of a preliminary interferometric study of optical quality expected from such resonators. This class of resonators is useful provided only that the output optical quality can be maintained at an acceptably high level. A more detailed, combined theoretical-computational study of expected optical properties has subsequently been performed. It forms the subject of this report.

This study considers the effect of one complete passage from convex to concave mirror on an initially collimated beam. This is essentially the conventionally aligned travelling-wave (or ring) resonator configuration. Standing-wave resonators, with or without beam inverters, are also of considerable interest, but they are not considered here. Both cases of relative sign of spherical-mirror tilt angles are considered; these are referred to as U and Z configurations. The Z configuration is preferred over the U configuration in optical quality.

A two-dimensional treatment (i.e., one which neglects one of the two transverse dimensions) is useful as a conceptual vehicle and as a means of obtaining useful, though only approximate, estimates of output beam quality. This is discussed first. A three-dimensional ray-tracing approach is then discussed and its predictions are compared with experiments. The most important part of this study is the experimental study, which is an extension and refinement of the preliminary interferometric study reported earlier.

II. THEORETICAL CALCULATIONS

A. Two-Dimensional Approximation

The two-dimensional approximation has the advantages of greater ease of detailed calculations, easier visualization, and feasibility of obtaining approximate closed-form predictions of optical

Cason, Charles, Jones, R. W., and Perkins, J. F., Optical Resonators with Tilted Spherical Mirrors, US Army Missile Research and Development Command, Redstone Arsenal, Alabama, September 1977, Report No. H-77-9.

²Cason, Charles, Jones, R. F., and Perkins, J. F., "Unstable Optical Resonators with Tilted Spherical Mirrors, "Optics Letters, Vol. 6, No. 2, June 1978, pp. 145-147.

quality. On the other hand, it is certainly not highly accurate quantitatively, and it sheds no light on the appearance of interferograms and their behavior with respect to variation of experimental parameters.

An approach based on local wave-front curvature was pursued first; this led to a closed-form approximate prediction of the magnitude of the principal contribution (the y^3 term) to the aberration resulting from tilting the spherical mirrors. The assumptions and approximations underlying this approach are perhaps obscure, so calculations were also carried out for one particular set of parameters using a ray-slope and an optical-path-difference (OPD) approach. The latter two calculations agreed with results of the former (local wave-front-curvature) approach, thereby lending it credibility.

The two basic types of configurations, U-type and Z-type, are illustrated in Figures 1(a) and 1(b). The basic design equations derived earlier make no distinction between these two types of design. The various treatments of aberrations as given here, however, clearly distinguish between the two types.

- 1. Wave-Front Curvature Approach. Figures 1(a) and 1(b) present the two basic types of configurations. The combination of mirror curvatures, separation, and tilt angles for the central ray will be chosen such that the curvatures in the y-z and x-z plane introduced at the convex mirror, after modification by passage to the concave mirror, (will be compensated by the concave mirror), and the emergent central portion of the beam will again be collimated. This condition will not be exactly satisfied for noncentral portions of the beam, as schematically related to off-center rays sketched in Figures 1(a) and 1(b). Behavior at noncentral portions of the beam between curved mirrors differs from that at the central position in two respects:
- a) The local tilt angles of the mirrors are slightly different from the central values.
- b) The distance between points of reflection by the two mirrors is slightly different for the off-center case.

The increments in tilt angles at the convex and concave mirrors, respectively, in going to an off-center case are labelled $\delta\theta_1$ and $\delta\theta_2$ initially. These two values are (approximately, but to a high order) equal. This can be shown as follows:

$$\frac{\delta\theta_1}{\delta\theta_2} = \pm \frac{\frac{a \sec \theta_1}{R_1}}{\frac{b \sec \theta_2}{R_2}} = \pm \frac{1}{\frac{1}{M_y}} \left(\frac{-R_2}{R_1}\right) \frac{\sec \theta_1}{\sec \theta_2},$$

$$= \pm \frac{M}{M_y} \frac{\sec \theta_1}{\sec \theta_2}.$$

From Equation (32)³, it is noted

$$\frac{M}{M_y} = \sqrt{\frac{M_x M_y}{M_y}} = \sqrt{\frac{M_x}{M_y}} .$$

By Equation (28)⁴, it follows that

$$\frac{M}{M_{v}} = \frac{\sec \theta_{2}}{\sec \theta_{1}} \qquad \bullet$$

Combining these two equations gives

$$\frac{\delta\theta}{\delta\theta_2} = \mp 1$$

The positive sign applies to the U configuration (from its shape); the negative sign applies to the Z configuration. For simplicity, δ is used to denote the common magnitude of $\delta\theta_1$ and $\delta\theta_2$.

a. Increment in Separation Required to Maintain Confocality: The basic confocality condition required to obtain collimation of the output beam in a localized region is

$$L_{\text{req}} (\delta = 0) = \frac{1}{2} \left[- |R_1| \cos \theta_1 + R_2 \cos \theta_2 \right]$$

The incremental value [i.e., change in L required to maintain confocality as the ray of interest moves from the center toward the upper

Op. cit., Cason et al., Optical Resonators . . .

⁴ Ibid.

portion of Figures 1 (a) and 1 (b)] can be obtained by expanding about the central angle. For the incremental ray, $\delta\theta_1$ is considered the negative of δ (i.e., δ is a positive quantity). This gives

$$\Delta L_{\text{req}} = \frac{1}{2} \delta \left[- |R_1| \sin \theta_1 + R_2 \sin \theta_2 \right]$$

b. Actual Increment in Separation of Reflection Points: First, only the difference in Z-coordinates of the points of reflection of a ray from each of the mirrors is considered. By geometrical construction, it can be seen that

$$\Delta Z \approx -\delta \left[-|R_1| \sin \theta_1 + R_2 \sin \theta_2 \right]$$

From separate numerical examination, it is found that the increment in path length due to the change in y coordinates is small compared to the preceding change in z coordinate. The incremental focal length then is the difference between these quantities, and it follows that

$$\Delta F = \Delta L_{req} - \Delta Z = \frac{3}{2} \delta \left[- |R_1| \sin \theta_1 + R_2 \sin \theta_2 \right]$$

c. Radius of Curvature of Emerging Wavelet: Next the local radius of curvature of the wave reflected from the concave mirror at the displaced position is determined for a mirror spacing adjusted such that the center portion of the emergent wave is collimated. From the lens equation, it follows that

$$\frac{1}{R_0} = \frac{1}{F_{2y}} - \frac{1}{(F_{2y} + \Delta F)} \approx \frac{\Delta F}{(F_{2y})^2}$$

where F $_{2y}$ is the y-coordinate effective focal length of Mirror 2 (concave mirror); namely, 1/2 R $_2$ cos θ_2 .

If it is assumed that the equation for the curve of constant phase (obtained by setting $\mathbf{x} = 0$ in the equation for the surface of constant optical phase) is

$$z - A y^3 = 0$$

the following is readily obtained:

$$\frac{d^2z}{dy^2} = 6 A y$$

By definition, the left-hand side of this equation is the reciprocal of the local radius of curvature. That is

$$\frac{1}{R_0} = 6 A y$$

Substitution in the preceding equation gives

$$z = \frac{1}{6 R_0} y^2$$

for the curve of constant phase. Introducing the earlier expression for \mathbf{R}_0 gives

$$z = \frac{2}{3} \frac{\Delta F}{R_2^2 \cos^2 \theta_2} y^2 \qquad ,$$

where ΔF is given by the preceding expression. Here y is used to denote the displacement at the output position; hence, y = R_2 $\delta \cos \theta_2$. Combining all of these gives

$$z = \frac{1}{R_2^3 \cos^3 \theta_2} \left[-|R_1| \sin \theta_1 + R_2 \sin \theta_2 \right] y^3$$

By inspection, the value of z for a given value of y is always smaller in magnitude for the Z configuration than for the U configuration. (Only the magnitude, but not the sign, of z as predicted by this equation is of significance, because the value of z has opposite signs for rays incident on opposite sides of the convex mirror).

As a numerical example, a case with R_1 = -290 cm, R_2 = 675 cm, θ_1 = 55°, y = 9.176 cm (corresponds to δ 0.01) is considered. The associated value of θ_2 is 38.76°. Using the preceding formula for the Z configuration, the following is obtained:

$$z = \frac{1}{(675 \times 0.77977)^3} \times 185.035 \times (9.176)^3 = 0.000 980 \text{ cm}$$

For the U configuration, the following is obtained

$$z = \frac{1}{(675 \times 0.77977)} \times (-660.144) \times (9.176)^3 = -0.003497 \text{ cm}$$

The expression for z as a function of y can alternatively be written as an explicit function of the magnifications M_x and M_y, rather than the angles θ_1 and θ_2 , although this has not been done here. There are equations from which θ_2 can be determined, when θ_1 , R₁, and R₂ are specified. 5

This detailed discussion has been given for the wave-front curvature approach in the y-z plane because it gives an explicit expression in terms of resonator parameters. Alternative approaches which have been used will be more briefly discussed. The function of the latter has been essentially limited to numerical and analytical confirmation of the preceding approach for one set of resonator parameters.

- 2. Ray Slope Approach. A two-dimensional ray-trace calculation was carried through numerically for the reference case with R_1 = -290 cm, R_2 = 675 cm, θ_1 = 55°; here the small parameter, again labelled δ (the distance between points of intersection of two incident rays with convex mirror and measured in units of radius of curvature of convex mirror) was treated. Numerical results agreed with the wave-curvature results. Treatment was done semi-analytically with various quantities expressed as expansions in powers of δ . From the latter, the y dependence of z (y dependence of slope) was confirmed as found from the wave-curvature approach.
- 3. OPD Approach. Direct numerical and semi-analytical expansion-type calculations were made to determine the OPD for the previously mentioned reference case. Results again confirmed the wave-curvature results.
- 4. Beam-Quality Predictions. Deterioration of the optical quality of the output beam is essentially determined by the root-mean-square (rms) value of variations in optical path length, z, measured in units of wavelength, relative to a suitable reference plane for a collimated output beam. The rms variations are considerably smaller than peak-to-peak or center-to-peak variations, and the choice of reference plane is important.

In the two-dimensional approximation, the center-to-peak variation, \mathbf{z}_{cp} , (approximately half the peak-to-peak variation) can be expressed as

$$z_{cp} \approx c_{03} y_{max}^3 = c_{03} y^3$$

⁵ Ibid.

where y_{max} is the half-width of the output beam, and C_{03} is a certain expansion coefficient (use of the double subscript is for consistency with the later three-dimensional calculations). From the preceding equation, the approximate prediction for C_{03} is

$$c_{03} \approx \frac{1}{R_2^3 \cos^3 \theta_2} \left[- |R_1| \sin \theta_1 + R_2 \sin \theta_2 \right]$$

The rms value for an untilted reference plane is obtained by simple integration

$$z_{\text{rms,nt}}^2 = \frac{\int_{y}^{y} [z (y)]^2 dy}{2y} = \frac{C_{03}^2}{2y} - \int_{y}^{y} y^6 dy$$

$$z_{rms,nt}^2 = \frac{1}{7} c_{03}^2 y^6$$
.

The factor of 7 reduction is naturally of considerable practical significance. It follows that

$$z_{rms,nt} = 0.378 z_{cp}$$

The preceding equations assume a reference plane which is perpendicular to the central ray of the output beam. There is no a priori reason why the reference plane must be so chosen. A reference plane which optimizes the beam quality can be chosen (i.e., to allow for a tilted reference plane (this is closely related to allowance for a tilted reference beam in interferometry, as discussed later), as given by the equation

$$z_{ref} = C_t y$$

The integral involved is

$$z_{\text{rms,t}} = \frac{1}{2y} \int_{y}^{y} \left[c_{03} y^{3} - c_{t} y \right]^{2} dy$$

= $\frac{1}{2y} c_{03}^{2} \int_{y}^{y} \left[y^{3} - B y \right]^{2} dy$

where

$$B = \frac{C_t}{C_{03}} \qquad \cdot$$

The following is readily obtained:

$$z_{rms,t}^2 = \frac{1}{7} c_{03}^2 y^6 f(B)$$

where

$$f(B) = 1 - \frac{14 B}{5 y^2} + \frac{7 B^2}{3 y^4}$$

To minimize f(B), its derivative is taken with respect to B and set equal to zero. The following is obtained:

$$B_{\text{opt}} = \frac{3}{5} y^2$$

The minimum value of f(B) is then

$$f_{opt}(B) = \frac{4}{25} = 0.160$$

This represents a further substantial reduction in the OPD which is effective in deterioration of beam quality. For optimal reference-plane tilt, the following is obtained:

$$z_{\text{rms,opt}}^2 = \frac{4}{175} c_{03}^2 y^6$$
 .

The minimized rms value itself can then be written as

$$z_{rms,opt} = 0.151 c_{03} y^3$$
.

This is less by a factor of approximately 13 than the peak-to-peak OPD. It is the square of this factor which is important in determining beam-quality deterioration.

Some numerical examples are given in Tables 1 through 3, which are representative of the mirror pair studied interferometrically: an example chemical-laser resonator design, and a ${\rm CO}_2$ pulsed electron-beam

laser, respectively. From these estimates, the optical quality should be quite acceptable at infrared wavelengths, when rms and reference-plane-tilt effects are accounted for, except for the rather extreme case of the mirrors being used for the interferometric testing in the case of Table 1. This pair of mirrors is considered at full aperture primarily because they provide useful interferometric structure at visible wavelengths, thereby, facilitating quantitative experimental studies of aberrations.

TABLE 1. TWO-DIMENSIONAL APPROXIMATE OPD PREDICTIONS (IN MICRONS) FOR A Z CONFIGURATION TRAVELLING-WAVE RESONATOR WITH R $_1$ = -290 cm, R $_2$ = 675 cm, Y = y $_{\rm max}$ = 7.62 cm, FOR VARIOUS VALUES OF CONVEX-MIRROR TILT ANGLE θ_1*

θ ₁ (deg)	z cp	zrms,nt	zrms,opt
10	0.393	0.149	0.059
20	0.855	0.323	0.129
30	1.481	0.560	0.224
45	3.168	1.198	0.479
50	4.165	1.574	0.630
55	5.614	2.122	0.849
60	7.866	2.973	1.189
65	11.709	4.426	1.770
70	19.233	7.270	2,908

*This corresponds to the resonator mirrors used in the interferometric study. The second column gives the center-to-edge values; the third column gives the rms OPD for an ultilted reference plane; the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

Such two-dimensional estimates would be considered quite uncertain if standing alone. In later sections of this report results of more detailed calculations will be presented. These rather simple sorts of estimates give useful semi-quantitative guidance to the expected degree of optical-quality degradation for an ideally aligned system. On the other hand, the two-dimensional considerations give no indication what-

TABLE 2. TWO-DIMENSIONAL APPROXIMATE OPD PREDICTIONS (IN MICRONS) FOR A Z CONFIGURATION TRAVELLING-WAVE RESONATOR WITH R₁ = -1481 cm, R₂ = 3703 cm, Y = y_{max} = 7.5 cm, FOR VARIOUS VALUES OF CONVEX-MIRROR TILT ANGLE θ_1 *

θ ₁ (deg)	z cp	zrms,nt	zrms,opt						
10	0.013	0.005	0.002						
20	0.028	0.010	0.004						
30	0.048	0.018	0.007						
45	0.100	0.038	0.015						
50	0.130	0.049	0.020						
55	0.174	0.066	0.026						
60	0.240	0.091	0.036						
65	0.352	0.133	0.053						
68.6	0.491	0.185	0.074						

*This corresponds to a typical MADS chemicallaser resonator. The second column gives the center-to-edge values; the third column gives the rms OPD for an untilted reference plane; the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

ever of the sensitivity of optical quality to various systems parameters, including increments to mirror separation L, and concave-mirror-tilt-angle θ_2 for a specified value of θ_1 .

The two-dimensional results give no information about expected shapes of interferograms. Using information gathered from experiments and three-dimensional calculations, a brief discussion of the behavior of reference-plane tilt can be given. In Figure 2, the $\rm C_{03}$ y dependence is plotted as a function of z in the solid curve. If the reference-plane is chosen to be that indicated by the dashed line, instead of the xy plane itself, the maximum OPD will clearly be reduced. If it is assumed that Z configurations have an $\rm x^2y$ term in the OPD series-expansion expression with the same sign as that of the y term, a

TABLE 3. TWO-DIMENSIONAL APPROXIMATE PREDICTIONS OF (IN MICRONS) FOR A Z CONFIGURATION TRAVELLING-WAVE RESONATOR WITH R₁ = -1180 cm, R₂ = 2640 cm, Y = y_{max} = 10 cm, FOR VARIOUS VALUES OF CONVEX-MIRROR TILT ANGLE θ_1*

θ_1 (deg)	z cp	zrms,nt	zrms,opt
10	0.057	0.022	0.009
20	0.124	0.047	0.019
30	0.216	0.082	0.033
45	0.468	0.177	0.071
50	0.619	0.234	0.094
55	0.839	0.317	0.127
60	1.184	0.448	0.179
65	1.778	0.672	0.269
70	2.952	1.116	0.446

*This corresponds to a typical ${\rm CO_2}$ E-beam laser.

The second column gives the center-to-edge values; the third column gives the rms OPD for an untilted reference plane; the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

qualitative property of an interferogram of an aligned system can be predicted with the reference beam tilted as shown by the dashed line.

The x^2y term will cause the OPD to increase for positive y when x is varied in either direction from zero, i.e., the surface for positive y will curve upward with respect to variations in x. Hence, tilted planes parallel to that indicated by the dashed line, but corresponding to smaller values of z, will intersect the surface in closed curves. Similarly, for negative values of y, tilted planes parallel to that indicated by the dashed line, but corresponding to larger values of z, will intersect the surface in closed curves. This is the qualitative nature of the interferograms for a suitable aligned system with tilted reference beam for Z configurations.

B. Three-Dimensional Calculations

The major portion of the theoretical-computational part of this study has been concerned with developing and applying three-dimensional ray-tracing computational methods and with correlating the results (primarily in the form of quasi-interferograms) with the experimental interferograms. The development of computational methods progressed from step-by-step hand calculations to the use of a programmable pocket calculator, then to a Fortran program which initially treated each of the spherical mirrors by a separate set of equations, and finally to a Fortran program which treats mirror reflections, ray intersections, and coordinate rotations by subroutines in such a way that possible future generalizations to more than two spherical mirrors should be simplified.

Equations employed in ray tracing are derived in Appendix A. Their present application assumes a collimated beam incident on the convex mirror. Given x and y coordinates of an incident ray measured relative to the central ray, the computer program calculates the path of the ray through the system and determines (a) direction cosines after reflection from the concave mirror, measured in a coordinate system with the positive z-axis parallel to the central ray and (b) the OPD between the ray considered and the central ray. The OPDs are of primary interest, and are calculated for a position close to the concave mirror. Double-precision arithmetic was used to obtain reliable values of OPDs.

The input data include half-widths of the desired output beam and the number of mesh points along x and y (usually 9 × 9) in the x and y directions. Coordinates x and y of incident rays are obtained by dividing corresponding desired coordinates of output rays by magnifications M and M, which are computed by the program from input values of R₁, R₂, and θ_1 . Unless otherwise specified, the program uses the values of mirror spacing L and concave-mirror tilt angle θ_2 which result in a collimated output beam. Values of these parameters are determined by an initial portion of the program. The first page of computer output is a table of calculated OPDs over the specified mesh; the OPDs are given in microns; mirror spacing and radii of curvature are given in centimeters.

As might be expected, there is a good deal of order in the calculated OPDs; their functional dependence on x and y can be well represented by a relatively small number of terms of a Taylor's expansion. The number of terms which are retained is somewhat arbitrary and has been increased from time to time. Terms \mathbf{C}_{03} y and \mathbf{C}_{21} are of primary importance. Values of the coefficients \mathbf{C}_{03} and \mathbf{C}_{21} are not the

same (as they may be in some contexts in which the terminology of "coma" is employed). The quadratic terms ${\rm C}_{20}$ x and ${\rm C}_{02}$ y can be important if the system is not properly adjusted. These terms have been included in the function-fitting process to be able to investigate the effects of adjusting L and ${\rm H}_2$ to values slightly different from their ideal values. A cross-term ${\rm C}_{22}$ x y and fourth-order terms of the form ${\rm C}_{40}$ x and ${\rm C}_{04}$ y are also considered.

The computer program evaluates the series coefficients from the table of calculated OPDs and prints these. It also calculates and prints a table of residuals showing the difference between the directly calculated OPDs and values obtained from the truncated series expansion; these typically seem to be of the order of less than one percent to few percent of the OPDs themselves. The coefficient C_{tilt} corresponding to a reference plane defined by $z = C_{tilt}$ y, which minimizes the rms OPD is also determined and printed. A table is printed (as the last page of output for each case) of the rms values of OPD for various values of reference-beam tilt measured in units of the optimal value. Inspection of this table indicates substantial reductions in the rms OPD, as would be expected from the discussion in connection with two-dimensional calculations. The even more pronounced reduction as compared to peak values of OPD can be seen by comparison to those listed in the OPD table.

If L and/or θ_2 are set to values incremented slightly from their proper values, there will be curvature in either or both the x and y directions, i.e., \mathbf{C}_{20} and/or \mathbf{C}_{02} will differ appreciably from zero. Expected values of these coefficients can be derived analytically and compared with results of the function-fitting process applied to the ray-tracing OPD calculations. This is discussed in Appendix B. Agreement between analytically predicted and "function-fitting" calculated values is felt to be a confirmation of proper functioning of the computer program.

The primary experimental data regarding optical quality from the tilted spherical mirror resonator are in the form of interferograms. While providing very precise and detailed information about the optical systems, interferograms do not immediately (without an intervening measurement and data-reduction process) lead to quantities predicted by the calculations. Therefore, it seemed useful to convert the calculated results into the form of computer-simulated quasi-interferograms. For this purpose the computer generates a fairly large array (usually 49×49) of OPDs obtained by evaluation of the truncated series expansion at each of the array points. The array of numerical values is converted

to an array of alphabetic characters or blanks and used to generate a one-page printer plot whose general apperance simulates that of an interferogram. Successive characters of the alphabet correspond to incremental OPDs of one wavelength (0.6328 μm). The interspersing of blanks with letters of the alphabet has the result that (at least in the central portion of the plot) light areas are interspersed with dark areas and properly simulate an interferogram. With only 26 characters available, the resolution is limited. As a result, it often happens that casual inspection of outer portions of such plots suggests spurious fringe pattern, because the eye tends to interpret contiguous light areas as all belonging to a light fringe. This difficulty can be avoided by concentrating on dark areas and keeping in mind that a particular dark fringe is always represented by the same letter of the alphabet. In one sense, the quasi-interferograms give more information than genuine interferograms because the sign and the magnitude of the OPD relative to the center are represented.

The computer program will optionally produce multiple quasi-interferograms corresponding to a specified set of reference-beam tilts from a single set of OPD calculations (Figures 3 through 14). The observed progression of shapes as tilt is systematically varied has proven interesting and useful because reference-beam tilt can also be varied experimentally. Inspection of quasi-interferograms leads to some interesting observations for a properly-aligned system (which was treated computationally prior to investigating effects of incremented values of L and $\boldsymbol{\theta}_2$):

- 1) There is symmetry in x, as would be expected since the entire optical system is assumed to have such symmetry.
- 2) For Z configurations and small-to-moderate values of θ_1 , the pattern is symmetric in y to a fairly high degree of approximation (the OPDs are approximately antisymmetric).
- 3) For Z configurations there is a regular progression of shapes as reference-beam tilt is increased from zero to its optimal value and beyond. Specifically, the pattern changes from a single central oval to a pair of ovals (symmetrically spaced about y = 0) which move further apart and are separated by an increasing number of fringes.

These observed properties are useful in experimental adjustment of L and θ_2 , because the symmetry in y is a rather good "signature". Calculations made with values of L and/or θ_2 which are incremented from their ideal values produce quasi-interferograms which are noticeably lacking in the y-symmetry property.

From one point of view, the tilted-spherical-mirror resonator concept can be described as a scheme in which a large degree of astigmatism is introduced by the tilt of the convex mirror, and is cancelled

by suitable choice of mirror spacing and the tilt of the concave mirror. Quasi-interferograms can be used to illustrate cancellation of curvature in either the x or y coordinates (simultaneous cancellation along both coordinates is achieved by the properly adjusted tilted-mirror resonator). For this purpose, a small value (10°) was chosen for θ_1 so that the effects to be illustrated would not be masked by other aberrations. The sequence of quasi-interferograms is presented in Figures 15 through 19. The basic case, i.e., the properly adjusted system, shows very little aberration of any sort; hence, it produces a rather structureless quasi-interferogram. When a small increment ΔL (labelled XINCL) in mirror spacing is introduced, curvature of the same sign is introduced along both x and y axes; the characteristic hill or valley shape is evident in Figure 16. Instead, if L is kept at its proper value but a small increment $\Delta\theta_2$ (labelled XINCT) to concave-mirror tilt is introduced, curvatures with opposite sign along the x and y axes are introduced. This leads to the characteristic "X" pattern representing a saddle-point type of surface, as seen in Figure 17. For a specified value of ΔL (or of $\Delta \theta_2$) an increment of the other parameter can be chosen, such as to cancel the curvature in either the x or y dimension. Such cases are presented in the Figure 18 and 19 plots, which show vertical and horizontal fringes. It should be emphasized that such cancellation could be obtained if there were additional sources of astigmatism present in the system. When one is free to adjust L and θ_2 , curvature can be eliminated in the x and y dimensions; i.e., coefficients C_{20} and C_{02} are reduced to zero. This is the criterion which defines the tilted-spherical-mirror resonator concept. It should emphasize that this cancellation can also be obtained if other sources of astigmatism are present. This small value of θ_1 was deliberately chosen to illustrate avoiding complicating the plots with substantial amounts of aberrations other than those associated with x^2 and y^2 expansion terms. For more realistic cases with larger values of θ_1 , the quasiinterferograms do not have such a simple appearance.

A number of calculations were made for θ_1 = 45° for various non-zero values of ΔL and $\Delta \theta_2$ (as well as reference-beam tilts); results are shown in Figures 20 through 43. The coefficient of either the x^2 or y^2 term can also be reduced to zero by suitable choice of one of the increments when the other is specified. Reduction to (approximately) zero of the C_{20} x^2 term shows up most clearly; the plot shows that there is very little OPD variation along x for y = 0. When the coefficient of y^2 is reduced to zero, the corresponding quasi

interferogram is somewhat more involved because there is still an appreciable amount of aberration present associated with other expansion terms. What is especially noticeable is that the y-symmetry is decidedly absent; this emphasizes usefulness of the y-symmetry property in making experimental adjustments. If the signs of ΔL and $\Delta\theta_2$ are reversed, the y^2 coefficient still vanishes, there is still a lack of y-symmetry, and the plot is essentially just the mirror image of the plot obtained without reversal of signs. This mirror-image property applies for any pair of magnitude of ΔL and $\Delta\theta_2$. In the special case of zero magnitude of these increments, the mirror image of the pattern is simply (to a rather good approximation) identical with the pattern itself; i.e., the y-symmetry property is characteristic of proper adjustment of L and θ_2 .

The y-symmetry property is not exact, though it seems to hold well for Z configurations (which are of greatest interest because they have fewer aberrations than U configurations) up to large values of θ_1 . Presumably, this property results from the fact that the principal terms in the series expansion of the OPD are of odd power in y (specifically, they are the y^3 and x^2y terms).

For cases where comparisons have been made, the three-dimensional ray-tracing calculations predict optical-quality parameters which are not greatly different from those obtained by the much simpler approach based on the two-dimensional approximation. Some specifics will be given in the following paragraphs.

For the representative MADS-type chemical-laser resonator with θ_1 = 68.6° and output-beam dimensions of 3 \times 15 cm, the detailed calculations give a center-to-peak OPD along the y-dimension (for x = 0) of approximately 0.49 μm , in agreement with the two-dimensional prediction of Table 2. The rms value of the OPD for an untilted reference plane is calculated to be 0.188 μm as compared to a two-dimensional prediction of 0.185 μm . The minimized (with respect to reference-plane tilt) rms value of OPD is calculated to be 0.075 μm as compared to the two-dimensional prediction of 0.074 μm . The agreement is rather good. This is partly due to the fact that the flow dimension is small compared to the cross-flow dimension, so that the resonator is, in fact, something of a strip.

For the typical CO $_2$ resonator at θ_1 = 55°, detailed calculations give a center-to-peak OPD along the y-dimension (for x = 0) of approximately 0.837 µm and a center-to-corner OPD of approximately 1.49 µm; by comparison the two-dimensional center-to-edge prediction of Table 3 is 0.839 µm. The rms value of OPD for an untilted reference plane is 0.448 µm compared to a two-dimensional prediction of 0.317 µm. The

minimized rms OPD is calculated to be 0.169 μm as compared to a two-dimensional prediction of 0.127 μm

For the mirror parameters associated with the experimental studies, calculations have been carried out for a range of values of θ_1 , for which the results are listed in Table 4.

TABLE 4. THREE-DIMENSIONAL RAY-TRACING PREDICTIONS (IN MICRONS) OF OPD FOR A Z CONFIGURATION TRAVELLING-WAVE RESONATOR WITH R_1 = -290 cm, R_2 = 675 cm, x_{max} = y_{max} = 7.62 cm, FOR VARIOUS VALUES OF CONVEX-MIRROR TILT ANGLE θ_1 *

θ_1 (deg)	z cp	z rms,nt	z rms,opt
10	0.393	0.230	0.091
20	0.855	0.496	0.194
30	1.481	0.848	0.330
45	3.171	1.764	0.678
50	4.171	2.287	0.876
55	5.626	3.031	1.157
60	7.892	4.159	1.582
70	19.450	9.529	3.667

*This corresponds to the resonator mirrors used in the interferometric study. The second column gives the center-to-edge values (taken along y for x = 0); center-to-corner values are somewhat larger but are not listed here. The third column gives the rms OPD for an untilted reference plane; the fourth column gives the rms OPD relative to an optimally-tilted reference plane.

These results may be directly compared with the two-dimensional predictions for the same case as given in Table 1. The three-dimensional predictions of the optimized rms OPD range from only 25% to 50% larger than the two-dimensional predictions, even for this case which is a resonator with larger aberrations.

The adjustment of L and θ_2 , when R_1 and R_2 are fixed and θ_1 is set, is a central feature of this resonator concept. As alluded to earlier, a significant aspect of the recent studies has been development of criteria and procedures for making the appropriate adjustments. The question naturally arises as to the quantitative degree of sensitivity of rms OPD to variations in L and θ_2 . Some numerical results are plotted in Figures 44 through 46. It was found that the numerically-determined values are in fairly good agreement with predictions that can be made on the basis of the intially somewhat questionable assumption that aberrations other than those of quadratic type are insensitive to adjustment of L and θ_2 , and that these other aberrations are odd in y and hence "noninteracting" with the quadratic aberrations introduced by variations in L and/or θ_2 . Following the approach of Appendix B, the ratio of the coefficients ${\rm C}^{}_{20}$ and ${\rm C}^{}_{02}$ to $\Delta {\rm L}$ and/or $\Delta \theta^{}_2$ can then be determined. With these assumptions, values of rms OPD can be predicted as a function of ΔL for $\Delta \theta_2 = 0$ and as a function of $\Delta \theta_2$ for $\Delta L = 0$. These predictions are plotted as the smooth curves in Figures 45 and 46. The numericallydetermined values agree satisfactorily with the curves. The OPD contributions from increments to L and to θ_2 are not additive (though the magnitude of the combined effect of specified increments to both parameters can be predicted).

For the system being studied experimentally at moderate values of θ_1 (45° and 55°), it appears that L should be adjusted to within a few millimeters, and θ_2 to within a few milliradians in order that wavecurvature effects not increase the overall aberration substantially beyond the minimal value which is inherent in the tilted-spherical mirror design. These are not very stringent restrictions on experimental adjustments.

III. EXPERIMENTAL RESULTS

The results of this section agree quantitatively with the computational results obtained in the three-dimensional calculations of wavefront OPDs. A set of mirrors was chosen to give a moderate number of fringes across the output aperture and could be compared directly to calculated quasi-interferograms. This test represented an extreme case compared to the aberrations which would be present in the proposed high aspect ratio resonator mirrors but provided a direct correlation between theory and experiment.

⁶ Ibid.

Two types of resonator concepts were tested, the Z configuration and the U configuration. The schematics of these configurations are shown in Figures 1(a) and 1(b). Most of the interferograms were taken with the Z configuration experimental setup. Only two photographs were taken in the U configuration. All agreed well with the analytical predictions of OPD.

Schematics of the experimental setup for the Z and U configurations are shown in Figures 47(a) and 47(b). In both cases a plane wavefront is produced by passing a helium-neon laser beam through a spatial filter (microscope objective plus pinhole) and collimating the resultant spherically divergent wavefront with a high quality objective lens of 6-in. diameter. This plane wavefront is then split into two components with a glass beamsplitter. One component (reference beam) is reflected directly into a focusing lens to a camera. The other portion (test beam) passes through the beamsplitter to the convex resonator mirror, reflects to the concave resonator mirror, and is directed back through the beamsplitter into the camera by means of appropriately positioned mirror flats.

To obtain the best quality interferograms, an alignment procedure for adjustment of the resonator mirrors is necessary. First, the angles $\theta_1,~\theta_2$ and the separation between the mirrors is setup in gross agreement with the theoretical predictions (Figure 1). With the reference beam blocked, the beam passing through the resonator and focusing lens is observed. The concave resonator mirror is tilted (variation of θ_2) with simultaneous compensation of the turning flat mirror to keep the beam on the optical axis of the focusing lens. The optimal setting of θ_2 is obtained with the sharpest focal point.

For any given value of θ_1 there is only one value of θ_2 and L which minimize the aberrations introduced in the tilted spherical mirror configurations. The mirror separation L is not as critical as θ_2 to set up experimentally. No variation from the theoretically determined value was necessary.

The interferograms were obtained by superimposing the focal points of the two beams from the beamsplitter (by tilting the turning flat). There is a certain arbitrariness in this adjustment— the interferogram obtained depends strongly upon the angle between the reference beam and the test beam (wavefront tilt). This variability made it difficult to compare exactly the quasi-interferograms obtained analytically with the experimental interferograms.

^{7&}lt;sub>Ibid</sub>.

Figures 48 through 54 illustrate the effect of variation of wavefront tilt (reference beam tilt) upon the appearance of the interferograms. A direct side-by-side comparison of theory and experiment is given in many of these and the following cases shown. The agreement is seen to be very good. These cases are for nominal alignment with θ_1 = 45° in the Z configuration. A vignetting of the 6-in. square theoretical OPD plots is a result of the concave mirror being tilted with respect to the optic axis (Figure 1). The mirror is round and when viewed from the output end (2b), it produces a test beam having an elliptical cross section of 6-in. major axis by 6 cos θ_2 in. minor axis. This has been taken into account by not drawing an interferogram in the portions of the theoretical plots not seen.

Effects of misalignments (ΔL , $\Delta \theta_2$) for θ_1 = 45° are shown in Figures 55 through 58. Figure 55 shows the result of a change in separation (ΔL) between the convex and concave mirrors (closer together by 1 cm). Figures 56 and 57 result from varying θ_2 approximately ±7 mrad ($\Delta \theta_2$) about the correct angular position. The mirror symmetry introduced about the vertical axis for $\Delta \theta_2$ of +7 mrad is evident in the interferograms. An increase in deviation of θ_2 of 14 mrad increases the aberrations as seen by the increased number of fringes in Figure 58.

The U configuration was tested for θ_1 = 45°. Figures 59 and 60 are interferograms obtained for two settings of reference beam tilt. The aberrations increase with increasing θ_1 as shown in Figures 61-74 for θ_1 = 70°. Figures 61-64 show a variation in reference beam tilt for the nominally aligned position of resonator mirrors. A comparison of this set of figures with the similar set at θ_1 = 45° (Figures 48 through 54 show that the essential features of the interferograms are the same, but that the aberrations are worse (more fringes) in the 70° case.

Variations in ΔL and $\Delta\theta_2$ for θ_1 = 70° show the same general features as for $\Delta\theta_1$ = 45°. Figures 65 and 66 are interferograms taken for ΔL = ± 2 cm variation about the nominal separation in spherical mirrors. Figures 67 and 68 show $\Delta\theta_2$ = ± 7 mrad. Figures 69 and 70 give a variation of $\Delta\theta_2$ = ± 14 mrad. The mirror symmetry of these interferograms in ΔL and $\Delta\theta_2$ is evident in the figures. These interferograms were taken in the Z configuration.

The interferograms for the U configuration show worse phase front errors than the Z configuration. Figures 71 and 72 are interferograms at θ_1 = 70° for two cases of reference beam tilt. These interferograms as well as the theoretical counterparts are not symmetric about the vertical axis. These are due to the higher order even terms contributing to the phase error in the series expansion of the OPD.

Figures 73 and 74 are a return to the θ_1 = 70°, Z configuration and show a tilt of the concave mirror out of the plane of rotation of θ_1 and θ_2 (in the vertical direction of +7 mrad). The mirror symmetry of the interferograms about the horizontal axis for these misalignments is seen.

IV. SUMMARY AND CONCLUSIONS

Advantages of this relatively new type of resonator have been noted earlier; these include asymmetric magnification (M $_{\rm X} \neq \rm M_{\rm y})$ combined with collimated output, a considerable measure of experimental and design flexibility, and the relative ease of fabrication and adjustment of spherical-figure mirrors (as used in the present designs) as constrasted to the case of toroidal mirrors (which are otherwise used to achieved asymmetric magnification). The disadvantages of tilted-spherical-mirror resonators is the additional deterioration of output optical quality resulting from the substantial mirror tilt angles which are involved; a quantitative investigation of this effect seemed clearly in order. Investigation of the optical quality is proceeding in stages. A preliminary interferometric investigation was already reported in connection with the initial examination of the resonator concept. 8,9

This study has considered in a rather detailed manner the effect on optical quality resulting from one complete passage from convex to concave mirror (essentially a conventionally aligned travelling-wave configuration) of an input collimated beam. Comparison of computational and experimental results has been facilitated by presenting computed results in a format similar in appearance to interferograms. Computational and experimental results, including shapes of interferograms and their behavior as a function of reference-beam tilt angle, incremental mirror separation, and incremental concave mirror tilt angle, are in satisfactory agreement. The considerable reduction in root-mean-square OPD which results from using a slightly tilted reference plane has been confirmed; this simply implies that in a practical device, a major

^{8&}lt;sub>Ibid</sub>.

⁹ Op. cit., Cason et al., Unstable Optical Resonators . . .

portion of the distinctive tilted-mirror effect consists of a slight angular displacement of far-field peak intensity relative to that of the nominal position. Small angular pointing errors are correctable by a tracker.

The experimental and computational studies have both clearly shown that the Z configuration is to be preferred over the U configuration as regards output optical quality. The principal tilted-spherical-mirror aberrations in a properly adjusted system arise from contributions to optical path differences which are proportional to y^3 and to x^2y . For a high-aspect-ratio resonator, only the y^3 contribution will be of substantial significance; the magnitude of this contribution was found to scale as y^3/R^2 . Formulas are given for determining the magnitude of this contribution in a one-transverse-dimension approximation without extensive numerical computations, though three-dimensional ray-tracing calculations are required to evaluate the detailed effects. Tables are given of results of approximate and detailed calculations for selected systems.

Certain additional aspects of this general class of resonators could be investigated by extensions of methods used in the present study. First, the effect of repeated propagation of a beam through the resonator (satisfying the round-trip consistency condition) should be investigated; this will include effects of decentered alignment. Secondly, and more importantly, the studies should be extended to somewhat more involved configurations than those considered here. In particular, an investigation needs to be made of standing-wave tiltedspherical-mirror configurations, which involve a more complex optical path including a turning flat or inverter associated with each of the two spherical mirrors. In such an investigation an effort should naturally be made to find methods of optimizing optical quality as well as achieving other desirable features (e.g., reduced sensitivity to laser-medium inhomogeneities). Distances between turning flats or inverters and their associated spherical mirrors are additional experimental variables, suitable adjustment of which may possibly lead to improvement of optical quality as compared to the travelling-wave configuration, as well as providing variations in magnifications M_{ν} and M_{ν} . An especially desirable goal in this connection is finding combinations of parameters such that aberration effects are reduced to very small magnitudes. While there is no compelling reason for expecting this to be possible, it cannot be ruled out in advance, particularly because in typical chemical-laser configurations, only the y aberration term should be of substantial significance.

The effects of beam inverters associated with either or both spherical mirrors in a standing-wave device should be investigated, not only as a possible means of reducing empty-resonator aberrations but also

because beam inversion could be quite helpful in reducing deleterious effects of spatial nonuniformity of gain and index of refraction in the laser gain medium. It is also desirable to investigate the latter effects separately, perhaps by wave-optics calculations and by experiments. The effects of beam inversion in travelling-wave resonators should also be considered; it should be noted that inversion in travelling-wave resonators can be accomplished with an odd number of flat turning mirrors without the necessity of special inverting optical components.

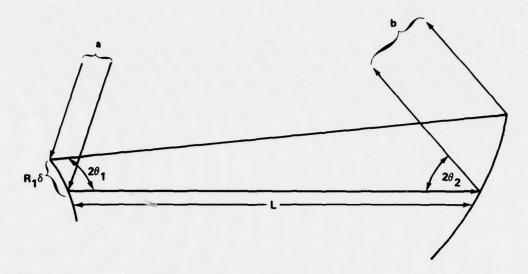


Figure 1(a). Schematic drawing of U configuration resonator.

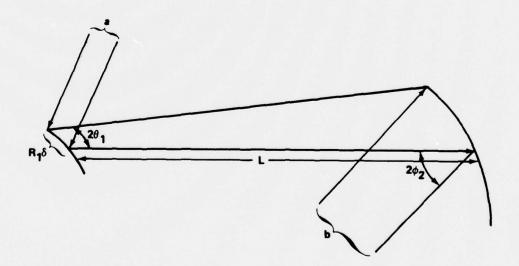


Figure 1(b). Schematic drawing of ${\bf Z}$ configuration resonator.

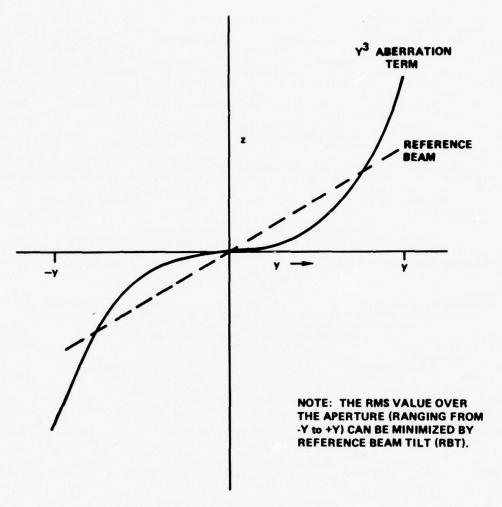


Figure 2. Dependence of the y^3 aberration term.

```
DDDD EEEE FF.
BB CCC DDDD EEE
                       EEEEEE DDDD CCC BR
FFFF EEEE DDDD CCC
FFFFF EEEE DDD
                 FFFFFF EEEE D
GGGGGGGGGGG FFFFF
HHHH GGGGGGG FFFFF
      нининин ос
                         GGGGG FFF
E FFF GGGGG
FFFF GGGG HHHH
            IIIIIIIIIIIIIIIII
       ннннн
  HHHHH IIIIII TUUN LIITII HHHHH
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   JJJJJJ KKKKKKKKKK
                    KKKKKKKKKKK 1111111
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                       KKKKKKKK JJJJJJ
JJJJJJ KKKKKKK
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ILLLLLLLLLLLL
 ILLLLLLLLLLL
                         LLLLLLLLLLLL
             МММММММММММММММ
LLLLLLLLLLLL
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        MMMMMMMMMMMMMMMMMMMMMMMMMMMMMM
                     NNNNNNNN
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  0000000
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PPP 000000000000
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                      YYY XXX
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Figure 3. Computer-generated quasi-interferogram Z configuration, $\theta_1 = 45^\circ$, nominal values of L and θ_2 , reference-beam tilt (RBT) (optimal value of RBT) = 0.222 (-0.370), in units of 10^{-4} rad.

```
FFFFFF EEEE DDD CCC
GGGGGGGG FFFFF EEE DDD
HHH GGGGGG FFFF EEE
HHHHHHHH GGGGG FFF EE
                    HHHHHHH GGGG FFI
TITITI HHHH

HHHHH

G
                  KKKKKKKKKK JJJJJJ IIIII
                     KKKKKKK
JJJJJ
                      KKKKKKK
KKKKKK
                           KKKKKK
 KKKKKKK IIIIIIIII
IIIIIIIIIIII
KK LLLLLLLL
                      LLLLLLLLLLLL
              MMMMMMMM
                        LLLLLLLLL
LLLLLLLLLL
          MMMMMMMMMMMMMMMMMM
NNNNNNNNNNNNNNNNN
                        NNNNNNNNNNNNNNNNNN
 NNNNNNNNNNNNNNNNNNNNNNNNNNNN
                   NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
   00000000
       0000000000
        000000000
  00000000
             NNNNNNNN
                         000000000
   000000000
Q PPPPPP 0000000000
                       000000000
                    00000000000
```

Figure 4. Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0.148 (-0.370).

```
E FFF FFFF
                      GGGGGG FFFF EEE DD
HH GGGG FFFF EEE
HHHHHHH GGGG FFF F
III HHHHH GGGG FFF
нн
                               нн
  KKKKKK JJJJJ
J KKKKKKK LLLLLLLL
                           KKKKKK JJJJ
                   LLLLLLLLLLLL
 LLLLLLLLLL
                             KKKKKK
KKKKK LLLLLL
                        LLLLLLLLL
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             мммммммммммммм
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     MMMMMMMMMMMMMMMMMMMMMM
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  NNNNNNNNNNNNNNNNNNNNNNN
                      NNNNNNNNNNNNNNNNNNNN
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      00000000
 00000000
        00000000
00000000
PPPPP 000000000
         000000000 PPPPP
                          00000000
9PPPPP 00000000
             NNNNNNNNNNNNNNN
                               PPPP
                       000000000 PPPPPP
20 PPPPPP 000000000
RRRR Q000
                     000000000
```

Figure 5. Z configuration, $\theta_1 = 45^\circ$, RBT = 0.074 (-0.370).

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FFF FFF
  rf GGGG
GGG
                                    GGGG FFF
HH GGGG FFF
HHH GGG FF
GGG
                              ннннн 6666
     IIIIIII
                                IIIII
                           KKKKKKKKKK JIJIJ II
KKKKKKK
JJJJJJ
                                 KKKKKK JJJJ IIII
                                   KKKKKK JJJJJ
JJJJ KKKKK LLLLLLL
                                      KKKKK JJJJ
                            LLLLLLLLLL
                                LLLLLLL
KKKKKK TITT
      LLLLLLL
                   MMMMMMMMMMM
                                  LLLLLLL
                                    LLLLLLL
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           LLLLLLL
LLLLLLL
         MMMMMMMMMMMMMMMMMMM
                                         LLLLLLL
LLLL
        MMMMMMMMMMMMMMMM
                            MMMMMMMMMMMMMMM
      MMMMMMMMMMMMMMM
                               MMMMMMMMMMMMMM
    MMMMMMMMMMMMMMMMM
                                МММММММММММММММММ
 MMMMMMMMMMMMMMMMM
                                  ММММММММММММММММММ
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MMMMMMMMMMM
                                       ММММММММММММ
MMM
NNNNNNNN
                                         NNNNNNNN
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                                    NNNNNNNNNNNNNNN
   NNNNNNNNNNNNNN
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     NNNNNNNNNNNNN
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      NNNNNNNNNNNNN
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       NNNNNNNNNNNNNN
                            NNNNNNNNNNNNNN
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 0000000
                        NNNNNNNNNNNNNNNN
         NNNNNNNNNNNNNNNNNNN
                                        0000000
   0000000
           0000000
                                     0000000 PPPPP
           0000000
                                   0000000 PPPPP
     0000000
0000000
QQQQ PPPP
PPPPP
              0000000 PPPPP
  000000000
000000000
0000
                   NNNNNNNNNN
   RRR
                                          RRR
```

Figure 6. Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0.000 (-0.370).

```
FFF GGG
                         | 11111 | 11111 | 11111 | 11111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 1111 | 111
                                                                                                                                                                                                               GGG
                                                                                                                                                         IIIIIII HHHHH GGG FFF
KKKKKKK JJJJ IIII
IIII HHH G
                                  KKKKKKKKK JJJJJJ
                                                                                                                                                                                   KKKKK JJJJ
                                                                                                                                                                                                                              1111
      JJJJ KKKKK LLLLLLL
                                                                                                                                                                                                                 11111
                                                                                    III
                                                                                                                                                                                           KKKKK
                                                                                                                                                                                                                          1111
                                                                                                                                     LLLLLLLLLLLL
JJJJ KKKK LLLLLL
                                                                                                                                                                                                                    KKKK 1111
                                                                                                                                                                                                         KKKKK
                                                                                                                                                                LLLLLLL
                                                                                                                                                                            LLLLLLLL
        KKKK LLLLLLL
                                                                                      LLLLLL
 KKKK LLLLLL
                                                                       LLLLLL
KK LLLLLL
                                                                                                                                     -
                                                              ММММММММММММММ
                                                                                                                                                                                                         LLLLLL
                                                      MMMMMMMMMMM
                                                                                                                                                       -
                                                                                                                                                                                                                  LLLLLLL
    LLLLLL
                                           -
                                                                                                                                                                  -
                                                                                                                                                                                                                           LLLLLL
                                      MMMMMMMMMM
                                                                                                                                                                           -
 LLLLL
                                                                                                                                                                                                                                   LLLLL
                              -
                                                                                                                                                                                 -
                      --
                                                                                                                                                                                         -
               -
                                                                                                                                                                                               -
      ммммммммммм
                                                                                                                                                                                                     -
 -
                                                                                                                                                                                                           -
 MMMMMMMMMM
                                                                                                                                                                                                                  -
 -
                                                                                                                                                                                                                                 -
```

```
NNNNNNNNN
NNNNNNNNN
                                         NNNNNNNNNNN
VNNNNNNNNNNN
                                        NNNNNNNNNNN
 NNNNNNNNNNN
  NNNNNNNNNNN
                                       NNNNNNNNNNN
    NNNNNNNNNN
                                     NNNNNNNNN
                                    NNNNNNNNN
    NNNNNNNNNN
00000
      NNNNNNNNN
                                   NNNNNNNNN
                                             00000
       NNNNNNNNNN
                                 NNNNNNNNN
000000
                                          000000
PP
000000
PP
SSS TTT UU
SS TTT UU
TTT UUU VV
```

Figure 7. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.074 (-0.370).

```
CCC HHHH IIIII 111111
JJJJJJJ IIIII HHHH GGG
                                                    TITLE KKKKK
 KKKKK LLLL MMMMMMM
KKKK LLL
                MMMMMMMMMM
                                                            KKKK
                                      MMMMMMMMMM
                                          MMMMMMMMM
                                                      LLLLLL
                                             MMMMMMMM
                                                         LLLLLL
          MMMMMMMM
                                               MMMMMMMM
LLLLL
        MMMMMMMM
                          NNNNNNNNNNNNN
                                                 MMMMMMMM
                                                             LLLLL
       MMMMMMMM
                        NNNNNNNNNNNNNNNNNN
                                                   MMMMMMMM
     MMMMMMMM
                       NNNNNNNNNNNNNNNNNNNNNNN
                                                    MMMMMMMM
    MMMMMMMMM
                      NNNNNNNNNNNNNNNNNNNNNNNNNN
                                                      MMMMMMMMM
  MMMMMMMMM
                     NNNNNNNNNNNNNNNNNNNNNNNNNN
                                                       MMMMMMMMM
MMMMMMMMMM
                     NNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                        ---
MMMMMMMMM
                      NNNNNNNNNNNNNNNNNNNNNNNN
                                                          MMMMMMMM
MMMMMMM
                       NNNNNNNNNNNNNNNNNNNNNNNN
                                                            MMMMMMM
MMMMM
                           NNNNNNNNNNNN
                                                             MMMMM
```

```
NNNNN
   NNNNN
   NNNNNNNN
                                                                                                                                                  MMMMMMMMMMMM
                                                                                                                                                                                                                                                                                                                     NNNNNNN
   NNNNNNNNN
                                                                                                                             NNNNNNNNN
      NNNNNNNNN
                                                                                                                      NNNNNNNNN
              NNNNNNNNN
                                                                                                                      MMMMMMMMMMMMMMMMMMMMMMMMMMMMM
                                                                                                                                                                                                                                                                                                 NNNNNNNNN
                   NNNNNNNN
                                                                                                                      МММММММММММММММММММММММММММММММ
                                                                                                                                                                                                                                                                                             NNNNNNNN
   0
                      NNNNNNNN
                                                                                                                      NNNNNNNN
   000
                                 NNNNNNNN
                                                                                                                             MMMMMMMMMMMMMMMMMMMMM
                                                                                                                                                                                                                                                                             NNNNNNNN
                                                                                                                                                                                                                                                                                                                                        000
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   00000
                                        NNNNNNNN
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          00000
                                                    NNNNNNN
                                                                                                                                                    MMMMMMMMMM
                                                                                                                                                                                                                                                                                                                      00000
                                                                                                                                                                                                                                        NNNNNNN ODDOG PPP
          PPP 00000 NNNNNNNN
                                                           NNNNNNN
| NUMBER | N
               00000
                                                                                                                                                                                                                                                                                                 00000 PPPP
      PPPP 00000
```

Figure 8. Z configuration, θ_1 = 45°, RBT = -0.148 (-0.370).

```
TELETICE KKKKK JJJ IIII
            ннн
    III
       11111
 TITTE KKKK
                                     III
     KKKK LLLLL
                MMMMMMMMMMMMM
                                    1111
  KKKK LLLLLL
             KKKK
                                     111
     ıııı
 KKKK
           MMMMMMMMM
                       MMMMMMMMM
                               LLLLL
                                   KKKK
         ммммммм
KKKK LLLLL
                          MMMMMMMM
                                 LLLLL
                                    KKKK
  LLLL
       MMMMMMM
                            MMMMMMM
                 NNNNNNNN
                                  LLLL
      MMMMMM
              NNNNNNNNNNNNNNNNNNN
                             MMMMMM
 LLLLL
                                   LLLLL
LLLLL
     MMMMMMM
             NNNNNNNNNNNNNNNNNNNNNNNNNNNN
                              MMMMMMM
                                    LLLLL
    MMMMMMM
           MMMMMMM
LLLL
                                     LLLL
   MMMMMMM
          MMMMMMM
LL
  MMMMMMM
          MMMMMMM
 -
         NNNNNNNNNNNNNNNN
                    NNNNNNNNNNNNNNNNN
                                  MMMMMMM
MMMMMMMM
         NNNNNNNNNNNNNNNNNNN
                    NNNNNNNNNNNNNNNNNN
                                   MMMMMMMM
-
        -
MMMMMMM
        MMMMMMM
-
        -
MMMM
        MMMM
MM
         NNNNNNNNNNNNNNNNNNNNNNNNNNN
```

```
NNNN
NNNNN
                                         NNNNN
NNNNNN
                                         NNNNNN
NNNNNNN
                                        NNNNNNN
NNNNNNNN
                                       NNNNNNNN
 NNNNNNN
                                       NNNNNNN
  NNNNNN
                                      NNNNNN
   NNNNNNN
                                     NNNNNNN
                                           0
   NNNNNN
            000
                                     NNNNNN
00000
     NNNNNN
             NNNNNN
                                         00000
     NNNNNN
 00000
              NNNNN
PPP 0000
                                        00000
                                       0000 P
                                 NNNNN
 PP 00000 NANNAN
      NNNNNN
PPP 0000
               МММММММММММММММММММММММ
0000 PP
```

Figure 9. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.222 (-0.370).

```
III JJJJ KKKK
            LLLLLL
                                       KKKK
                                 LLLLLL
                                           JJJJ III
     KKK LLLLL
                МММММММММММММММММММММММММММ
                                         KKK
                                             111
                                    LLLLL
                              MMMMMMMM
       LLLL
             -
                                      LLLL
                                           KKKK
                     NNNNNNNNNNN
                                        LLLL
                                    MMMMMM
    LLLL
         MMMMMM
                                          LLLL
                NNNNNNNNNNNNNNNNNNNNNNNNNN
                                              KKK
       MMMMM
                             NNNNNNNNNN
  LLLL
             NNNNNNNNNN
                                      MMMMM
                                            LLLL
            NNNNNNN
                                NNNNNNN
                                        MMMMM
                                             LLLL
                                          MMMMM
          NNNNNNN
                                  NNNNNNN
                                              LLLL
   MMMM
         NNNNNNN
                   00000000000000000000
                                           MMMM
                                    NNNNNNN
LL
                                                LL
  MMMM
                 NNNNNN
                                      NNNNNN
                                             MMMM
       NNNNNN
               NNNNNN
                                              MMMM
     NNNNNN
               MMMM
                                       NNNNNNN
MMM
    NNNNNNN
              NNNNNNN
    NNNNNNN
             NNNNNNN
   NNNNNN
             NNNNNNN
  NNNNNNN
             NNNNNNN
 NNNNNNNN
              NNNNNNNN
              NNNNNNNN
                                           NNNNNNNN
NNNNNNNNNN
                NNNNNNNNNN
NNNNNNNNNNN
                    0000000000000000
                                          NNNNNNNNNNN
NNNNNNNNNNN
                                          NNNNNNNNNNN
NNNNNNNNNNNN
                                         NNNNNNNNNNNN
NNNNNNNNNNNNNNNN
                                       NNNNNNNNNNNNNNNN
NNNNNNNNNNNNNNNNNNNNNNNNNNNNN
NNNNNNNNNNNNNNNNNNNNNNNNNNN
                                NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
NNNNNNNNNNNNNNNN
                                      NNNNNNNNNNNNNNNNN
NNNNNNNNNNNNN
                                        NNNNNNNNNNNNNN
NNNNNNNNNNN
                                         NNNNNNNNNNNN
 NNNNNNNNNN
                                          NNNNNNNNNN
                    MMMMMMMMMMMMM
                 ММММММММММММММММММММММММММ
 NNNNNNNNN
                                          NNNNNNNNN
  NNNNNNNN
               NNNNNNNN
  NNNNNNN
                                          NNNNNNN
   NNNNNNN
                                         NNNNNNN
    NNNNNNN
              00
                                        NNNNNNN
                                                00
0000
     NNNNNNN
              0000
                                        NNNNNNN
0000
     NNNNNN
              NNNNNNN
                                              0000
 00000
               NNNNNN
                                       NNNNN
                                             00000
  00000
        NNNNNN
                 ммммммммммммммммммммммм
                                      NNNNNN
                                            00000
   00000
                  ММММММММММММММММММ
                                           00000
         NNNNNN
                                    NNNNNN
                                         00000 PF.
    00000
          NNNNNNN
                     MMMMMMMMMM
                                   NNNNNNN
                                        0000 PPP
      0000
           NNNNNN
                                 NNNNNN
    PPPP 00000
              NNNNNNN
                              NNNNNNN
                                       00000
       PPPP 000000
         00000
               00000
                                        PPPP GGG
                  NNNNNNNNNNNNNNNN
                                   000000
  999
     9999 0000000
18 000
                                OOOOOOO PPPP QQQ RR
PPPPP QQQ RR S:
   999
            SS
               999
                                              SSS
          0000
```

Figure 10. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.296 (-0.370).

```
LLLL
                             MMM LLLLL KKKK J
MMMMMM
               KKKK
      LLLLL
   KKKK
                          MMMMMMMM
                               MMMMM LLLL KKKK
                                        111
 KKKK LLLL
                  NNNNNNNNNNN
                                         J
                                 MMMMM LLLL KKK
   וווו
        MMMMM
              NNNNNNNNNNNNNNNNNNNNNNNNN
  LLLL
      MMMMM
                        NNNNNNNNN
            NNNNNNNNN
                                      LLLL
 LLLL
                                  MMMMM
     MMMMM
          NNNNNNN
                            NNNNNNN
         NNNNNNN
                             NNNNNNN
                                    MMMM
LLLL
                                       LLLL
   MMMM
        NNNNNN
                NNNNNN
                                     MMMM
LLL
                                         LLL
  MMMM
       NNNNNN
               NNNNNN
                                      MMMM
 MMMMM
                                      -
      NNNNNN
              NNNNNN
MMMMM
     NNNNNNN
             NNNNNNN
                                       MMMMM
MMMMM
    NNNNNN
             NNNNNN
                                        MMMMM
MMM
    NNNNNN
            NNNNNNN
                                         MMM
MM
    NNNNNNN
            NNNNNNN
                                         MM
   NNNNNNN
             NNNNNNN
   NNNNNNNN
             NNNNNNNN
   NNNNNNNN
               NNNNNNNN
   NNNNNNNNNN
                   000000000
                                  NNNNNNNNNN
  NNNNNNNNNNN
                                 NNNNNNNNNNNN
   NNNNNNNNNNNNNN
                               NNNNNNNNNNNNNNN
   NNNNNNNNNNNNNNNNNNNNNN
```

```
МММММММММММММММММММ
                                   MMMMMMMMMMMMMMMMM
     MMMMMMMMMMMM
                                      MMMMMMMMMMMM
     MMMMMMMMMM
                                        MMMMMMMMMM
     MMMMMMMMM
                       LLLLLLL
                                         MMMMMMMMM
     -
                   MMMMMMMM
     MMMMMMMM
NN
                 ..........
                                          MMMMMMMM
                                                   NN
     MMMMMMM
                ..........
                                          MMMMMMM
                                                  NNN
NNNN
      MMMMMMM
                MMMMMMM
                                                 NNNN
NNNNN
      MMMMMM
                MMMMMM
                                                NNNNN
 NNNNN
       MMMMMM
                LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL
                                         MMMMMM
                                                NNNNN
  NNNN
        MMMMMM
                 .........
                                        MMMMMMM
                                               NNNN
00
         MMMMMM
   NNNN
                                       MMMMMM
                                              NNNN
                  0000
    NNNN
          MMMMMM
                    MMMMMM
                                            NNNN
                                                 0000
                                          NNNN UN PPP
 0000
      NNNN
           MMMMMM
                                    MMMMMM
                       LLLLLLLL
                                                0000
                               MMMMMMM NNNN 0000 PF.
MMMMMMM NNNN 0000 PPP QF
NNNNNN 0000 PPP QG
00 PPP QQ
      NNNN
  0000
            MMMMMMMM
PPP
   000
             -
        NNNNN
NNNNNN OOOU
NNNNNNN OOOU
NN OOOO PF
                                                 999
                                           PPP QQ
                                               Q RR
```

Figure 11. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.370 (-0.370).

```
LLLL
 J KKK LLLL MMM
KKK LLLL MMMM
            MMMMM
                      NNNNNNNNNNNNNNNNNN
                                          MMMMM
                                                LLLL
                                                     KKK
                 NNNNNNNNN
                                 NNNNNNNNN
                                             MMMM
   LLL
                                                  LLLL
                                                       KKK
KK
               NNNNNNN
                                       NNNNNNN
                                               MMMM
                                                    LLL
 LLL
            NNNNNN
                       000000000000000000
                                                 MMMM
                                          NNNNNN
                                                       LLL
LLL
          NNNNNN
                    MMMM
                                           NNNNNN
                                                        LLL
                 000000000000
                            00000000000
         NNNNN
                                                     MMM
LL
                                             NNNNN
                                                          LL
  MMM
                0000000000
        NNNNN
                                                      MMM
                                    0000000000
                                               NNNNN
 MMMM
              000000000
      NNNNN
                                      000000000
                                                 NNNNN
                                                       MMMM
             000000000
MMMM
     NNNNN
                                        000000000
                                                  NNNNN
                                                        MMMM
    NNNNN
            00000000
                                         00000000
                                                   NNNNN
                                                          MM
    NNNNN
           000000000
                                         000000000
                                                    NNNNN
   NNNNN
           000000000
                                         000000000
                                                    NNNNN
  NNNNN
           0000000000
                                         0000000000
                                                     NNNNN
  NNNNNN
           00000000000
                                        00000000000
                                                     NNNNNN
 NNNNNNN
           000000000000
                                       000000000000
                                                     NNNNNN
            00000000000000000
                                   00000000000000000
NNNNNNN
                                                     NNNNNNN
              NNNNNNN
                                                     NNNNNNN
               NNNNNNNNN
                                                    NNNNNNNNN
NNNNNNNNNN
                   NNNNNNNNNN
NNNNNNNNNNNNN
                                                 NNNNNNNNNNNN
NNNNNNNNNNNNNNNN
                                               NNNNNNNNNNNNNNN
 NNNNNNNNNNNNNNNNNNNNNNNNN
```

```
мимимимимимимимимимимим
                                     MMMMMMMMMMMMMMMMMMMM
  мммммммммммм
                                           MMMMMMMMMMMMM
  MMMMMMMMMM
                                              MMMMMMMMMM
  ммммммммм
                                               MMMMMMMMM
                  MMMMMMMM
              MMMMMMMM
  MMMMMMM
                                                MMMMMMMM
             MMMMMM
            LLLLLLLLLLLLLLLL
                                                 MMMMMM
                                LLLLLLLLLLLLLLLL
  MMMMMM
                                                 MMMMMM
           LLLLLLLLLLLL
                                    LLLLLLLLLLLL
   MMMMMM
           LLLLLLLLL
                                     LLLLLLLLL
                                                MMMMMM
    MMMMM
           LLLLLLLL
                                      LLLLLLLL
                                                MMMMM
NN
    MMMMM
                                                MMMMM
           LLLLLLLL
                                      LLLLLLLL
                                                      NN
NNNN
     MMMMM
                                               MMMMM
            LLLLLLL
                                      LLLLLLL
                                                     NNNN
     MMMMM
                                              MMMMM
NNNN
                                                    NNNN
             LLLLLLL
                                     LLLLLLL
      MMMMM
                                    LLLLLLL
 NNNN
                                             MMMMM
                                                   NNNN
              LLLLLLL
       MMMM
                                  LLLLLLLLL
                                            MMMM
   NNN
               LLLLLLLLL
                                                 NNN 000
                                                  NNN
 NNN MMMMM
OOO NNNN MMMMMM
P 000 NNNN MMMMMM
PP 0000
000
                 LLLLLLLLLL
                               LLLLLLLLLL
                                           MMMMM
                                                      000
                                                NNN
PPP 000
 000
                  MMMMM
                                       MMMMMM
                                              NNNN
                                                  000
                                                      PP
                     OOOO NNNN MMMMMM
                                MMMMMMM NNNN 000
                                            NNNN 000
      PP
                                                      Q
                                      NNNNN 0000
QQQ PPP
                                                 PPP QQQ
RR QQQ PPP
                                                PPP QQQ RR
```

Figure 12. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.444 (-0.370).

E ZOOM HE SELVEN WORK SET WITH

```
MMMM
           NNNNNN
KKK LLL
                   00000000000000000
                                  NNNNNN
                                            LLL
               LLL
    MMMM
         NNNNN
                                    NNNNN
                                         MMMM
                                             LLL
LLL
   MMM
       NNNNN
             00000000
                              00000000
                                      NNNNN
      NNNN
            0000000
                                0000000
                                       NNNN
                                            MMMM
 MMMM
     NNNN
          000000
                    PPPPPPPPPPPPPP
                                  000000
                                        NNNN
                                             MMMM
MMM
    NNNN
         00000
                 00000
                                          NNNN
                                              MMM
                                           NNNN
   NNNN
        000000
                РРРРРРРРРРРРРРРРРРРРРРРР
                                    000000
  NNNNN
       000000
               000000
                                           NNNNN
 NNNN
      000000
               000000
                                             NNNN
 NNNN
      000000
              000000
                                             NNNN
NNNN
      000000
              000000
                                              NNNN
NNNNN
     0000000
               0000000
                                              NNNNN
NNNN
     0000000
               NNNN
                                       0000000
NNN
     00000000
                00000000
                                               NNN
     000000000
                   PPPPPPPPPPPPPPPP
NNN
                                      000000000
                                               NNN
      0000000000
                                     0000000000
                                               NNN
NNN
NNNN
      0000000000000
                                  0000000000000
                                              NNNN
NNNN
        000000000000000000
                              000000000000000000
                                               NNNN
NNNNN
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              NNNNNNN
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NNNNNNNNNNNNNNNN
                                      NNNNNNNNNNNNNNNN
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```

```
ммммммммммммммм
                                            ммммммммммммммм
-
                                                MMMMMMMMMMMM
-
                                                  MMMMMMMMM
                MMMMMMMM
                                                    -
            MMMMMMM
                                                    MMMMMMM
          LLLLLLLLLLLLLLLLLL
                                   MMMMMM
MMMMMM
         LLLLLLLLLLL
                                       LLLLLLLLLLLL
MMMMMM
        LLLLLLLL
                                          LLLLLLLL
                                                     MMMMMM
MMMMMM
        LLLLLLL
                       KKKKKKKKKKKKKK
                                           LLLLLLL
                                                     MMMMMM
MMMMM
                                                     MMMMM
        LLLLLL
                    KKKKKKKKKKKKKKKKKKKKKKK
                                            LLLLLL
 MMMM
        LLLLL
                  KKKKKKKKKKKKKKKKKKKKKKKKK
                                             LLLLL
                                                     MMMM
 MMMMM
                                                    MMMMM
        LLLLLL
                  KKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                             LLLLL
 MMMMM
                                                    MMMMM
        LLLLLL
                  KKKKKKKKKKKKKKKKKKKKKKKKK
                                            LLLLLL
   MMMM
        LLLLL
                  KKKKKKKKKKKKKKKKKKKKKKKKKK
                                            LLLLL
                                                   MMMM
   MMMM
                                                  MMMM
         LLLLL
                                            LLLLL
    MMMM
          LLLLL
                   KKKKKKKKKKKKKKKKKKKKK
                                           LLLLL
                                                      NNN
 NNN
     MMMM
          LLLLLL
                     KKKKKKKKKKKKKKKKK
                                         LLLLL
  NNN
       MMMM
            LLLLLL
                       KKKKKKKKKKKKKK
                                        LLLLLL
000
        MMMM
              LLLLLL
                                                   NNN
                                                       000
                                      LLLLLL
                                                      000
 000
     NNN
         MMMM
                LLLLLLL
                                   LLLLLLL
                                            MMMM
                                                  NNN
                                       MMMM NNI
   000
      NNN
           MMMM
                  NNN
                                                   000
                                                        PP
 PPP 000 NNNN MMMMM
                                                 000 PPP
                       MMMMMMM
  PP
      OOO NNNN
                                   MMMMMMM
                                               000 PP QQ
                                           NNNN
```

Figure 13. Z configuration, $\theta_1 = 45^\circ$, RBT = -0.518 (-0.370).

```
0000
 MMM
    NNNN
                 PPPPPPPPPP
                            PPPPPPPPPPP
                                        0000
                                              NNNN
   NNN
        0000
                                  PPPPPPPP
                                          0000
                                               NNN
                                                   MMM
       0000
            PPPPPPP
                       000000000
                                    PPPPPPP
                                            0000
      000
           PPPPPP
                    0000000000000000000000
                                      PPPPPP
                                              000
                                                  NNN
    0000
         PPPPPP
NNN
                  PPPPPP
                                              0000
                                                   NNN
NN
   0000
         PPPPP
                PPPPP
                                                0000
                                                     NN
               909999999999
   0000
       PPPPP
                          000000000000
                                          PPPPP
                                                0000
 0000
       PPPPP
               000000000000
                               000000000000
                                           PPPPP
                                                 0000
 0000
      PPPPP
               000000000000
                               000000000000
                                           PPPPPP
                                                  0000
00000
      PPPPP
               000000000000000
                             999999999999
                                            PPPPP
                                                  00000
               PPPPPP
00000
                                            PPPPPP
                                                   00000
00000
      PPPPPPP
               PPPPPPP
                                                   00000
0000
      PPPPPPPP
                 PPPPPPPP
                                                   0000
0000
      PPPPPPP
                    PPPPPPPP
                                                   0000
       PPPPPPPP
00000
                                        PPPPPPPP
        PPPPPPPPPP
00000
                                      PPPPPPPPPPP
                                                   00000
0000000
          0000000
             00000000
                                                 00000000
00000000000
                 0000000000
 00000000000000
                                           00000000000000
   NNNNNNNNNNNNNNNNNNNNN
                                       NNNNNNNNNNNNNNNNNNNN
NNNNNNNNNNNNNNNNNNNNNNNNN
                                       NNNNN
NNNNN
               ММММММММММММММММ
                                     MMMMMMMMMMMMMMMM
   MMMMMMMMMM
                                           MMMMMMMMMMM
 MMMMMMMMM
                  MMMMMMMMM
 MMMMMMMM
             MMMMMMMM
 MMMMMMM
          LLLLLLLLLLLLLLLL
                                MMMMMMM
MMMMMM
         LLLLLLLLLL
                                                 MMMMMM
                                     LLLLLELLLLL
MMMMMM
        LLLLLLL
                                                  MMMMMM
                                        LLLLLLL
 MMMMM
        LLLLLL
                     KKKKKKKKKKKKKKKKK
                                                  MMMMM
                                         LLLLLLL
 MMMMM
       LLLLLL
                  KKKKKKKKKKKKKKKKKKKKKK
                                                  MMMMM
                                          LLLLLL
 MMMMM
                 KKKKKKKKKKKKKKKKKKKKKKKKK
                                                  MMMMM
       LLLLLL
                                           LLLLLL
 MMMM
       LLLLL
                KKKKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                           LLLLL
                                                  MMMM
  MMMM
        LLLLL
                KKKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                           LLLLL
                                                 MMMM
   MMMM
        LLLLLL
                KKKKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                          LLLLLL
                                                MMMM
NNN
   MMMM
        LLLLLL
                 KKKKKKKKKKKKKKKKKKKKKKKKK
                                                MMMM
                                                    NNN
                                         LLLLLL
    MMM
                 KKKKKKKKKKKKKKKKKKKKKKKK
                                               MMM
         LLLLL
                                         LLLLL
 NNN MMMM
          LLLLLL
                   KKKKKKKKKKKKKKKKKKKKK
                                       LLLLLL
                                              MMMM
                                 LLLLLL MMMM NNN
LLLLLLLL MMMM NNN
NNN OI
                                                NNN
  NNN
      MMMM
                     KKKKKKKKKKKKKKKK
                                                    00
           LLLLLL
                                             NNN OO
                         KKK
000 NNNN MMMM
                                               NNNN 000
            LLLLLL
           OOO NNN MMMM
                                                  000
PPP 000
      NNN MMMM
                                                    PPP
    OOO NNN
                                          NNN 000
```

MMM

Figure 14. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.592 (-0.370).

МММММММММММММММММММММММММ ММММММММММММММММММММММММ ММММММММММММММММММММ мммммммммммммммммммм -**МММММММММММММММММ** -**ММММММММММММ** MMMMMMMMMM ммммммммм MMMMMMMM MMMM

000

000

Figure 15. Z configuration, θ_1 = 10°, RBT = 0, nominal values of L and θ_2 , i.e., ΔL = 0, $\Delta \theta_2$ = 0.

NANNANNANNANNANNANNANNANNANNANNAN

RRRRRR SSSS TTT UUU SSSSSS RRRRRRR SSSSS UUU VV UUU VV SSS TTT UUU AKR SSS RRRR SSS TT UU TT RRRR SSS TTT Q RRR SSS TT QQ RRR SS T 99999 РРРРРРРР 000 RRR PPPPPP 9999 TT PPPPP TT 000000000000000 999 PPPPP 900 RR 00000000 00000000 PPPP 999 RR PPPP 0000000 999 000000 PPPP 000 RRR 55 RR GG PPPP 00000 NNNNNNNNNN 00000 PPPP 99 RR QQQ PPP RR QQQ PPP 55 PPP 00000 NNNNNNNNNNNNNNNN 00000 PPP 000 RR 0000 NNNNNNNNNNNNNNNNNNN 0000 PPP 000 RR RRR 0000 NNNNNNNNNNNNNNNNNNNNNNNN 0000 PPP 999 00 RR QQ PPP 00000 NNNNNNNNN NNNNNNNNN 00000 PPP RR 900 PPP 0000 NNNNNNN NNNNNNN 0000 PPP 000 RR QQQ PPP 000 NNNNNNN NNNNNNN 000 PPP 000 RR 90 PPP 0000 NNNNNNN NNNNNNN 0000 PPP QQ RR RRR GG PPP 0000 NNNNNN NNNNNN 0000 PPP 00 RRR PPP RR 90 PPP 0000 NNNNNN NNNNNN 0000 QG RR PPP QQQ 9.9 999 PPP 0000 NNNNNN NNNNNN 0000 RR 900 PPP 000 NNNNNNN NNNNNNN 000 PPP QQQ RR 99 RR PPP 0000 NNNNNNN NNNNNNN 0000 PPP 00 RR

Figure 16. Z configurations, θ_1 = 10°, RBT = 0, ΔL = 1.3097 cm, $\Delta \theta_2$ = 0.

O NN MM LLL KKKK JJJJJ IIIIII HHHHHHHHHHHH IIIII JJJ KKKK LLL MM NN MM LLL KKKK JJJJ IIIIIII HHHHHHHHHHHH IIIII JJJ KKK LLL MM NN MM LLL KKK JJJ IIIII KKKKK KKKKKK LLLL MMM NNN 00 P KKKKKKKKK LLLL LLLL MMM NN 00 PP MMM NNN 000 PP MMM NN 00 PPP Q NN 00 F. LLLLL MMMM MMMM NNN LLLLLLL Q PP 000 NNN MMMM
QQ PP 000 NNN MMMM
QQ PPP 000 NNN MMM
R QQ PPP 000 NNN MM
RR QQ PPP 000 NNN MM MMMM NNN 000 PP 'GQ MMM NNN 000 PPP 'GQ NNN 000 PPP QQ MMMM LLLLLLLLLLLLLLLL MMMMM MMMMM MMMMMMM MMMMMMM 000 PPP QQ R NNNN 000 PPP QQ RR MMMMMMMM NNN NNNN NNNN MMMMMMMM NNN RR QQ PP 000 RR QQ PP 000 RR QQ PPP 000 000 PP QQQ MMMMMMMMMMMMMMMMMMMMMMM NNNN MMMMMMMMMMMMMMMMMM NNNN 000 PP QQ RR PPP QQ 000 NNNNN MMMMMMMMMMMMM NNNNN 000 00 QQ PPP RR NNNNN MMMMMMMM NNNNN 000 PPP GQ RR PPP QQ S RR QQ QQ PPP NNNNN 0000 NNNNN 0000 RR 000 PPP NNNNNN NNNNNN 000 PPP RR S 0000 NNNNNN RR QQ PPP NNNNNN 0000 PPP QQ PPP RR 000 0000 NNNNNNN NNNNNN 0000 PPP QQQ ... PPP PPP GGG RR 000 0000 NNNNNN NNNNNN 0000 RR PPP PPP 000 RR 000 000 NNNNNN NNNNNN 000 RR PPP RR 000 0000 NNNNNN NNNNNN 0000 PPP 000 RR 20 000 PPP 0000 NNNNNNN NNNNNNN 0000 PPP 000 RR RR QQ RRR QQ PPP PPP 0000 NNNNNN NNNNNN 0000 00 RR PP 000 NNNNNN NNNNNN 000 PP 00 RRR RR QQQ PPP PPP 0000 NNNNN NNNNN 0000 000 PP 0000 QQ MMMMMMMM RR NNNNN NNNNN 0000 PP 99 RR RR GGQ PPP 000 NNNN
RR GG PP 000 NNNN MM
RR GG PP 000 NNNN MM
RR GG PP 000 NNNN MMMM
R GG PPP 000 NNNN MMMMM
GQ PPP 000 NNNN MMMMMM
GQ PPP 000 NNNN MMMMMM
CO PP 00 NNN MMMMM L GGG RR ммммммммммммм NNNNN PPP 000 MMMMMMMMMMMMMMMMMMM PP NNNN 000 **ММММММММММММММММММММММММ** PP 000 PP QQ NNNN NNNN MM ммммммм ммммммм NNNN MMMMMM NNNN OOO PPP QQ MMMMMMM MM NNNN 000 PPP QQ MMMM NNN 000 PPP Q MMMMM NNNN 000 PPP LLLLLLLLLLLLLLLLL 00 GQ PP OO NNN MMMM G PP OO NNN MMMM MMMM MMMM NNN 00 PP (ווווווו LLLLLL LL KKKKKKKKKKKKKKKKK LLLL MMM NNN 000 PP
KKKKKKKKK LLLLL MMM NN 00 PP
KKKKKKKKK KK LLLL MMM NNN 00 PP KKKK LLL MM NN 000 KKKKK LLL MMM NN 00 KKKK LLL MMM NN 00

Figure 17. Z configuration, $\theta_1 = 10^{\circ}$, RBT = 0, $\Delta L = 0$, $\Delta \theta_2 = -0.04233$ rad.

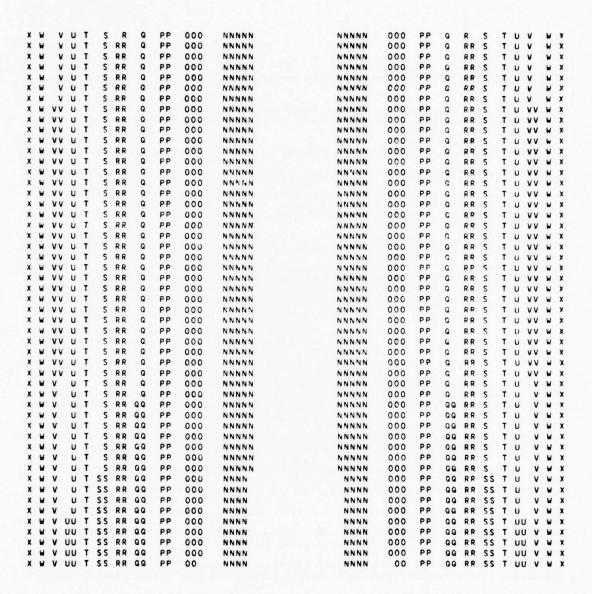
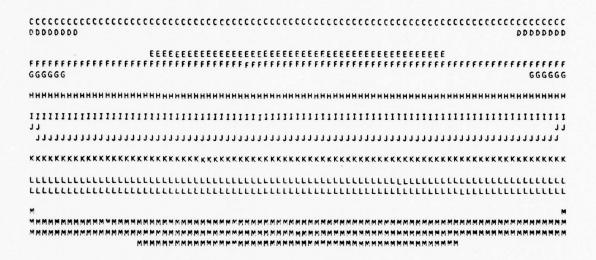


Figure 18. Z configuration, θ_1 = 10°, RBT = 0, ΔL = 1.3097 cm, $\Delta \theta_2$ = -0.04233 rad. The curvature along the y-coordinate has been reduced to approximately zero.



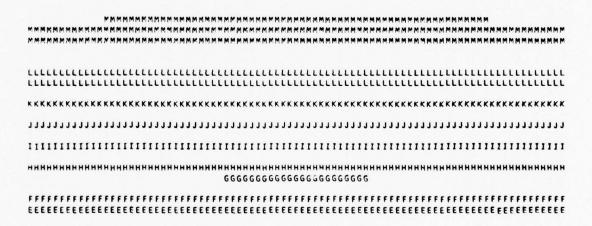


Figure 19. Z configuration, θ_1 = 10°, RBT = 0, ΔL = -1.333 cm, $\Delta \theta_2$ = -0.04233 rad. The curvature along the x-coordinate has been reduced to approximately zero.

```
мммммммм
```

NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN MMMMMMMM

NNNNNNNNNNNNNNNNNNNNNNNNN

NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN

NNNNNNNNNNNNNNNNNNNNNNN

NNNNNNNNNNNNNNNNNNNNNNNN

NNNNNNNNNNNNNNNNNN NNNNNNNNNNNN

NNNNNNNNNNNNNNNNNN NNNNNNNNNNN

```
00000
                                                                   00000
00000000
                                                                 00000000
000000000
                                                                000000000
000000000
                           NNNNNNNNNNNNNNNNN
                                                               000000000
0000000000
                       NNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                              0000000000
 000000000
                      NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                              000000000
  000000000
                    NNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                             000000000
   00000000
                   00000000
    0000000
                  0000000
    000000
                 NNNNNNNNNNNNNNNNN
                                   NNNNNNNNNNNNNNNNN
                                                             000000
     000000
                 NNNNNNNNNNNN
                                          NNNNNNNNNNNN
                                                            000000
PP
     000000
                NNNNNNNNNNN
                                            NNNNNNNNNNN
                                                            000000
PPP
      000000
                NNNNNNNNNN
                                             NNNNNNNNN
                                                            000000
PPPP
       00000
                 NNNNNNNN
                                              NNNNNNNN
                                                            00000
PPPP
        00000
                 NNNNNNNN
                                              NNNNNNNN
                                                           00000
        0000
                  NNNNNNN
                                              NNNNNNN
                                                           0000
   PPP
          0000
                  NNNNNNNN
                                             NNNNNNNN
                                                          0000
   PPPP
          0000
                  NNNNNNNN
                                            NNNNNNNN
                                                         0000
                                                                PPPP
QQQ
    PPPP
           0000
                    NNNNNNNN
                                           NNNNNNNN
                                                        0000
                                                               PPPP
                                                                     000
     PPP
           00000
                     NNNNNNNNN
                                         NNNNNNNNN
                                                      00000
          PPPP
  000
                      NNNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                      0000
                                                            PPPP
                                                                  000
   QQQ PPP
                                                    00000
                                                            PPP QQQ
RRR QQQ
         PPPP
                                                 00000
                                                         PPPP
                                                               QQQ RRR
      RR QQQ PPPP 0000C0
  S RR QQQ
SS PP
    SSS RRR QQQQ PPPPPP
T SS RRR QQQQ PPP
   VV UU TTT SSSS RRRRR QQQQQQQQQQQQ
IW VV UU TTT SSSS RRRRRRRR RRRRRRRR
                                            RRRRR SSSS TTT UU VV WW
 WW VV UU TTT SSSS RRRRRRRR XX W VVV UU TTT SSSSS Y XX WW VV UUU TTTT SSSSSSY XX WW VV UUUU TTTTTTTT
                                                 SSSS TTT UU VV WW
S TTT UU VVV W XX
TTT UUU VV WW XX Y
                                            SSSSS
                                                 UUUU VV WW XX
                                                TTTT
                            SSSSSSSSSSSSSSS
                                      TTTTTTTT
         XX MMM AAAA
                        UUUUU
                                          UUUUU
                                                  VVVV WWW XX YY
         YYY XX
                 -
                      VVVVV
                                            VVVVV
                                                       XX YYY
                                                   WWW
                 XXX
                      -
                                            -
                                                   XXX
                                                        YY
                 YYY
                      XXXX
                                 WWWWW
                                             XXXX
                                                   YYY
                       ***
```

Figure 20. Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0 (-0.379), $\Delta L = 1.0$ cm, $\Delta \theta_2 = 0$.

```
0000000000000000000000
                                         99999999999999999
  0000000000000
                                                0000000000000
                    00000000000
                                                    0000000000
              00000000
                                                      96999999
000000
          РРРРРРРРРРРРР
                                                        000000
0000
        PPPPPPPPPPP
                                            РРРРРРРРРР
                                                         9999
      PPPPPPPP
                     00
                                                PPPPPPPP
                                                           00
     PPPPPPP
                PPPPPPP
    PPPPPP
             00000000000
                                      000000000000
                                                   PPPPPP
           000000000
   PPPPP
                                          000000000
                                                     PPPPP
   PPPPP
          0000000
                       NNNNNNNNNNNNNNNN
                                             0000000
                                                      PPPPP
  PPPPP
         000000
                   NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                               000000
                                                      PPPPP
  PPPP
        000000
                 NNNNNNNNNNN
                                  NNNNNNNNNNN
                                                000000
                                                       PPPP
  PPP
        0000
               NNNNNNN
                                      NNNNNNNN
                                                 0000
                                                        PPP
  PPP
       0000
              NNNNNN
                                         NNNNNNN
                                                  0000
                                                        PPP
  PPP
       0000
             NNNNNN
                         -
                                          NNNNNN
                                                  0000
                                                        PPP
  PPP
      0000
             NNNNNN
                       МММММММММММММММММММ
                                           NNNNNN
                                                   0000
                                                        PPP
  PPP
      0000
             NNNNN
                     NNNNN
                                                   0000
                                                        PPP
                     000
   PP
       000
            NNNNN
                                             NNNNN
                                                        PP
                    PPP
       000
            NNNNN
                                             NNNNN
                                                   000
                                                       PPP
       000
   PPP
             NNNN
                    NNNN
                                                  000
                                                       PPP
                    ----
 00
    PP
             NNNNN
                                            NNNNN
                                                  0000
                                                       PP
                                                          00
       000
                                                 000
                                                     PPP QQ
 QQ PPP
             NNNNN
                     NNNNN
     PP 000
 QQ
    PP
              NNNNN
                      ----
                                          NNNNN
                                                 000
                                                     PP 00 R
 RR QQ PP 0000 NNNNN
RR QQQ PPP 000 NNNNN
; RR QQ PP 000 NNNN
iS RR QQ PP 000 NNNN
                       -
                                         NNNNN
                                               0000
                                                    PP
          PP 000 NNNNN
                                        NNNN
                                     NNNNN 000
MMMMMMMMM
                                              000
                                                  PPP QQQ RR
                                             000 PP QQ RR
                                   NNNNNNN
                                               PP QQQ RR
                                         0000
                                       00000
                                             PPP QQQ RR
                                                        55
                                               000
                                           PPP
                                                   RR SS TT U
                                              RRR SS TT UU VV
                                       PPPP QQQ RR
                                          000
                                       9999
                                            RR SS
                                                    TT UU VV W
                                        RRRR SS TT UU VV W XX
IRR SSS TT UU V WW XX
SSS TT UU VV WW XX Y
TTTT UU VV WW XX Y
UUU VVV WW XX Y
                                    RRRRR
                                     SSSS
```

Figure 21. Z configuration, θ_1 = 45°, RBT = -0.379 (-0.379), ΔL = 1.0 cm, $\Delta \theta_2$ = 0.

```
JJ KKK LLLL
JJ KKKK
              MMMMMMMM
   KKKK
        LLLLL
                               MMMMMMMM
                                        LLLLL
                                             KKKK
       LLLLL
              MMMMMMMM
                                MMMMMMMM
                                              KKKK
                                         LLLLL
             -
  KKKK
       LLLLL
                                 MMMMMMMM
                                               KKKK
                                         LLLLL
 KKKK
      LLLLL
             MMMMMMMM
                                 MMMMMMMM
                                          LLLLL
                                               KKKK
                                                KKKKK
KKKKK
      LLLLL
             MMMMMMMMM
                                 MMMMMMMMM
                                           LLLLL
KKK
            LLLLLL
                                 MMMMMMMMM
                                           LLLLLL
                                                 KKK
    LLLLL
            MMMMMMMMM
                                 MMMMMMMMMM
                                           LLLLLL
    LLLLLL
            M M M M M M M M M M M
                                MMMMMMMMMMM
                                           LLLLLL
    LLLLL
             LLLLL
             LLLLLLL
                                            LLLLLL
             LLLLLLL
                                            LLLLLLL
              LLLLLLL
 LLLLLLLLL
LLLLLLLLL
                LLLLLLLLL
LLLLLLLLLL
                LLLLLLL
                    MMMMMMMMMMMMMMMMMM
LLLLL
                                                LLLLLL
```

Figure 22. Z configuration, θ_1 = 45°, RBT = 0 (-0.361), L = -1.0 cm, θ_2 = 0.

```
II JJ KKK LLL MMMMM
I JJ KKK LLL MMMMM
JJ KKK LLL MMMMM
JJ KKK LLL MMMMM
                                          11
                                      KKK
                 NNNNNNNNNNNNNNN
                               MMMMM
                                   LLL
                               MMMMM
                                          11
                 NNNNNNNNNNNNNNNNNN
                                    LLL
                                       KKK
11
               ***********
                                           11
                                MMMMM
                                     LLL
                                        KKK
  KKK LLLL
         MMMMM
               MMMMM
                                     LLL
                                        KKK
                                            11
 KKK
         MMMMM
               **********************
                                 MMMMM
                                     LLLL
                                         KKK
         MMMMM
               LLL
                                 MMMMM
 KKK
                                      LLL
                                          KKK
 KKK
         MMMMM
                NNNNNNNNNNNNNNNNNNNNN
                                 -
    LLLL
                                      LLLL
                                          KKK
                NNNNNNNNNNNNNNNNNNNN
                                 -
 KKK
         MMMMMM
     LLLL
                                      LLLL
                                          KKK
 KKK
         MMMMMM
                 NNNNNNNNNNNNNNNNN
                                MMMMMM
                                          KKK
     LLLL
                                      LLLL
         MMMMMM
                   NNNNNNNNNN
                                MMMMMM
 KKK
                                          KKK
     LLLL
                                      LLLL
          MMMMMMM
                               MMMMMMM
 KKK
                                          KKK
     LLLLL
                                     LLLLL
           MMMMMMMM
                             MMMMMMMM
 KKKK
                                          KKKK
     LLLLL
                                     LLLLL
            мммммммммм
                          MMMMMMMMMM
 KKKK
                                    LLLLL
                                          KKKK
     LLLLL
             KKKKK
                                   LLLLLL
                                         KKKKK
      LLLLLL
                MMMMMMMMMMMMMMMMMMM
 KKKKK
       LLLLLLLL
                                 LLLLLLL
                                         KKKKK
  KKKKKK
        LLLLLLLL
                                LLLLLLLL
                                        KKKKKK
                             LLLLLLLLLL
  KKKKKK
         LLLLLLLLLL
                                        KKKKKK
   KKKKKKKK
           KKKKKKKK
               KKKKKKKK
                                     KKKKKKKK
    KKKKKKKKKKK
                                  KKKKKKKKKKK
      KKKKKKKKKKKKK
LLL
                               KKKKKKKKKKKKK
                                           111
         LLLL
                                           LLLL
TITITI
            KKKKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                         1111111
11111111111
                                       111111111111
111111111111111111
                                   LLL
          LLL
1111
         LLLL
TITITI
         111111
11111111
         11111111
 1111111
          1111111
```

Figure 23. Z configuration, θ_1 = 45°, RBT = -0.361 (-0.361), ΔL = -1.0 cm, $\Delta \theta_2$ = 0.

```
UUUUU
         TTTTTTTTT
                                             TTTTTTTTT
                                                          UUUUU
      UUU
                                              TTTTTTT
                                                           UUU
    TITITIT SSSSSSSSSS
                                                   TTTTTTT
                                        $22222222
                                                     TTTTTT
           $$$$$$$$
                           RRRRRRRRR
                                           SSSSSSSS
        SSSSSS RRRRRRRRR
                   $$$$$$
 TTTTT
                                                        TTTTT
       SSSSS
 TITI
                                      RRRRRRRRRR
                                                   SSSSS
                                                         TTTT
TTTT
      SSSS
                                                     SSSS
    SSSS RRRRR DUGGES RRRRR QQQQQQQ
                      PRPRRR
                                                      SSSS
   SSS
                 0000000000
                                   00000000000
                                                       555
   SSS
                                        0000000
                                                  RRRR
                                                        SSS
      RRRR GGGQ
  222
             000000
                       РРРРРРРРРРРРРРРРРР
                                           000000
                                                        SSS
     SSS RRE QQUA
SSS RRR QQUA
OR QQQ PPER
OR QQQ PPPPP
                   РРРРРРРРРРРР РРРРРРРРРР
                                             00000
                                                     RRRR
SSS RRR
                                    РРРРРРРР
                                               0000
                                         PPPPPP
                                                 000
SSS HRR GGGG
                                           PPPPP
                                                  0000
000000000 000000000
                                             PPPPP
                                                   0000
                                    0000000
                  0000000
                                              PPPP
                                                   000
                                                        RRR
                                       000000
                000000
                                               PPPP
                                                    000
                                                        RRR
                                                    QQ
              00000
                        NNNNNNNNNNNNNNN
                                         00000
               0000
                      NNNNNNNNNNNNNNNNNNNNNN
                                           0000
             0000
                     NNNNNNNNNNNNNNNNNNNNNNN
                                                 PPP
                                            0000
                   NNNNNNN
                             NNNNNNN
                                                 PP
              0000
                                            0000
                                                     QQQ RR
                                                 PP
              000
                   NNNNNNN
                                            000
                                                     00
NNNNNN
                                             000
                                                 PPP
              000
                    NNNNNN
                                     TTT UU V WW X

TTTT UU V WW X Y

UUUU VVV WW XX Y

VVVV WW XX Y

WWWW XXX YY

XXXX YY
              XX WW
                    VVVV
                            UUUUUUU
                XXX
                     -
                          V V V V
                     XXXX
                      7777
                                    ***
```

Figure 24. Z configuration, θ_1 = 45°, RBT = 0 (-0.389), ΔL = 2.0 cm, $\Delta \theta_2$ = 0.

Figure 25. Z configuration, $\theta_1 = 45^\circ$, RBT = -0.389 (-0.389), $\Delta L = 2.0$ cm, $\Delta \theta_2 = 0$.

```
888888888888
                                    cccccccccccccc
                 AAAAAAAAAAAAAAAA BB
AAAAAAAAAAAA BB CCC DDDD
C DD EE FF GG
MMMM LLLL KKK 3-

MMMMM LLLL KKK 3-

MMMMM LLLL KKKK JJJ III H

LLLLLL KKKKK JJJ III H

HHH

JJJ III HHH

HHH

HHH
                     MMM
              LLLLL
  III JJJ KKKK
  II
           KKKKK LITITI
                   KKKKKKK JIJI III

TITITITITITI KKKKKK JIJI III

TITITITITITITITITITI KKKKK
                           ıııııııı
          KKKK
      1111
HH III
                 LLLLLLLLL
            KKKKK
                      TITLE TOTAL KKKKKKK JIJJ IIII

TITLETTETTETT KKKKKKK JIJJ III
   III
       1111
             KKKKKK
   111 111
HHH
               KKKKKKK
        1111
ннн
                     III
                 KKKKKKKKKKKKK KKKKKKKKKK
          11111
                                         линнн нинн нинн нинн нинн нинн нинн
 ннн
           111111
 HHH
     IIII
                                                      HHH
      1111
             1111111
  нннн
               11111111111
        IIIII
  нннн
         IIIIII
                                           IIIIII
    нннн
                   IIIIIIII НИНИНИ
НИНИНИ
           IIIIIIII
GGG
    ннннн
                                                 ннннн
     ннннн
             11111111111
                                   IIIIIIIIII
GGGG
      ннинин
                                             нининин
                 GGGGG
                                          ннинини
        нининини
 GGGGGG
                          IIIIIII
                                      нинининин сесове
Сесове
                                                    666666
         нинининини
  GGGGGG
                                                   GGGGGG
             нинининин Соссосс
нининининининининининининининин Соссосс
    GGGGGGG
     GGGGGGGG
FF
                                          66666666666
       GGGGGGGGGG
```

Figure 26. Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0 (-0.351) $\Delta L = -2.0$ cm, $\Delta \theta_2 = 0$.

```
888888
                  888888
AAAAAAAAAAAAAAAA BB CC
                      CCCC
                   CCCC
AAAAAAAAAAAAA BB
           DDDD
                    DDDD
                         BB AAAAAAAAAAAAAA
BB AAAAAAAAAAAA
AAAAAAAAAAAA BB CC
        DDD
           EEEE
                       DDD CC
                    EEEE
         LLL KKK JJ II
 II JJ KKK LLL
              NNNNNNNNNN
                     MMMMM
               NNNNN
KKK JJ
                     -
                        LLL
  888886
```

Figure 27. Z configuration, θ_1 = 45°, RBT = -0.351 (-0.351), ΔL = -2.0 cm, $\Delta \theta_2$ = 0.

```
G H I J KK
                                000000000000000
            KK LL
                        NNN
                                                   NNN
                                                                KK JJ II H
                   MMM
                               00000000000000000
                                                   NNNN
                                                         MMM
               LL
                        NNNN
                                                             LL
   H I JJ
                               00000000000000000
                                                                 K K
               LL
                        NNN
                                                    NNN
                                                             LL
                                                                       I HH
                   MM
                                                         MM
             LL
                        NNN
                               00000000000000000
                                                    NNN
                                                              LL
                                                                    JJ I
                  MMM
     II JJ KK
                        NNN
                               00000000000000000
                                                    NNN
                                                              LL
     I JJ KK
                  MMM
                               00000000000000000
                                                    NNN
                                                         MMM
              LL
                        NNN
                                                              LL
                                                                  KK JJ
           KK
                  MMM
                               00000000000000000
                                                    NNN
                                                         MMM
              LL
                        NNN
                                                                  KK
                                                              LL
  H II
                  MMM
                                                   NNNN
                                                         MMM
                                                                        II H
           KK
                        NNNN
                                000000000000000
                                                                  KK
              LL
                                                              LL
                  MMM
                                 0000000000000
                                                   NNNN
                                                         MMM
G HH II JJ
           KK
                        NNNN
              LL
                                                              LL
                                                                  KK
G HH
                   MM
                                  0000000000
                                                  NNNN
                                                         MM
           KK
                                                                  KK
    II JJ
                        NNNN
                                                                     JJ
              LL
                                                              LL
                   MMM
                        NNNN
   II JJ
           KK
              LL
                                     00000
                                                  NNNN
                                                        MMM
                                                              11
                                                                  KK
                                                        MMM
                   MMM
           KK
                                                 NNNN
       JJ
              LL
                          NNNN
                                                              LL
                                                                 KK
                   MMMM
                                                        MMMM
       11
           KK
              LLL
                         NNNNNN
                                               NNNNNN
                                                             LLL
                                                                 KK
                    MMM
                          NNNNNN
                                                       MMM
       JJ
           KK
                                              NNNNNN
                                                                 KK
                                                                     JJ
              LLL
                                                             LLL
       JJ
           KK
                    MMMM
                           NNNNNNN
                                           NNNNNNN
                                                      MMMM
               LL
                                                                  KK
                                                                     JJ
                                                             LL
       JJ
           KK
                     MMM
                            NNNNNNNNNNNNNNNNNNNNN
                                                      MMM
                                                                 KK
   II
               LLL
                                                            LLL
                                                                     JJ
           KKK
                     MMMM
                              NNNNNNNNNNNNNNNN
       11
                                                      MMMM
                                                                 KKK
   II
               LLL
                                                            LLL
                                                                     JJ
                                                                         II
       11
           KKK
                      MMMM
                               NNNNNNNNNNNNNNN
                                                                 KKK
   II
               LLL
                                                            LLL
                                                                     11
                                                                         II
           KKK
                      MMMMM
                                 NNNNNNNNNNN
       11
                                                                 KKK
   II
                LLL
                                                           LLL
                                                                     JJ
                                                                         II
нн
           KKK
                       MMMMM
                                   NNNNNNNN
                                                   MMMMM
   II
       JJ
                LLL
                                                                 KKK
                                                                     11
                                                           LLL
                                                                         II
  II
                       MMMMM
       JJ
           KKK
                LLL
                                                           LLL
                                                                 KKK
                                                                     JJ
                        MMMMM
           KKK
                                                                 KKK
  II
      111
                LLLL
                                                          LLLL
                                                                     111
                                                                          ΙI
  II
           KKK
     JJ
                LLLL
                                                          LLLL
                                                                 KKK
                                                                      JJ
 II
      JJ
           KKK
                                                                 KKK
                                                                      JJ
                                                                           II
                LLLL
                                                          LLLL
     JJJ KKK
                                                                     111
                LLLL
                                                          LLLL
     11
         KKK
                                                MMMMMMM
               LLLL
                                                                       11
                                                           LLLL
                                                ммммммм
         KKK
               LLLL
                                                           LLLL
                                                 MMMMMMM
       KKK
              LLLL
                                                            LLLL
                                                   MMMMMM
             LLLL
                                                             LLLL
                    MMMMMMM
                                                    MMMMMMM
      KKK
            LLLL
                                                              LLLL
                                                      MMMMMM
          LLLL
        LLLL MMMMM
                              NNNNNNNNNNNNNNNN
                                                        MMMMM
                                                                 LLLL
      LLLL
                          NNNNNNNNNNNNNNNNNNNNNNNN
                                                           MMMMM
    LLLL
           MMMMM
                       NNNNNNNNN
                                              NNNNNNNNN
      MMMM NNNNNN
                              0000000000000000000
                                                        NNNNNNN
                                                              NNNNN MMM.
     M NNNN 00
                       00000000
     0000000
                        0000000 NNNN
                                                                    000000
   000000
                                                     PPPPPPPPP
                        PPPP
           0000000000
                                                         0000000000
9999999
                RRRRRRRRRRRRRRRRRRR
                                            RRRRRRRRRRRRRRRRRRR
  RRRRRRRRR
                        $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
                                                                    RRRRRRRRR
   SSSSSSSSSSS
                                                                SSSSSSSSSSS
   ***********
                                                            TTTTTTTTTTTTTTT
  UUUUUUUUUUUUUUUUUUUUUU
vvvvvvvvvvvvvvvvvvvvv
                                                         VVVVVVVVVVVVVVVVVVVVVVV
```

Figure 28. Z configuration, θ_1 = 45°, RBT = 0 (-0.392), $\Delta L = 0$, $\Delta \theta_2 = 0.007$ rad.

```
SSSS RRR QQ PP U III
                      SSSS
                                 TTT
        O PP QQ RRR
K LL M
            PP
               QQ
                  RRR
                       SSSSSS
         CO PP QQ
  LL
                                    SSSSSS RKK
                                       SSSSSS
                         SSSSSSS
       NN 00
            PP
               QQ
                   RRR
            PP QQQ RRR
                          $$$$$$$$$$$$$$$$$$$
                                                  QQQ PP O NN MM LL K
  LL MM NN
       N
          00
            PP QQQ
                     RRRR
                                           RRRR
                                                 QQQ PP 00
                              SSSSSSSSSS
  L M NN O PP QQQ RRRR
LL MM N OO PPP QQQQ RRRRI
L M NN OO PPP QQQ RI
LL MM NN OO PPP QQQQ
                                       RRRR GGG PP O NN M L
RRRRRR GGG PPP OO N MM LL
RRRR GGG PPP OO NN M L
KK
                       RRRRRR
                         RRRRRRRRRRRRRR QQQQ PPP OO NN MM LL KK J
QQQQQ PPP OO NN MM LL KK J
QQQQQ QDQQQQQQ PPPP OO NN MM LL KK JJ
QQQQQQQQQQQQQQQQQQQ
PPPP OOO NN MM LL KK JJ
PPPPP OOO NNN MM LL KK JJ
  K LL MM NN OO PPP QQQQQ
K LL MM NN OO PPPP QQQQQQQ
KK LL MM NN OOO PPPP QQQQQQQQQQQQ
K LL MM NNN OOO PPPPP
 KK LL MM NN
     PPPPPPP 000
                                                     NNN MM LL KK JJ
                                               0000
                                                    NNN MM
    KK LL
                                               0000 NNN MM LL KK JJ
NNNN MM LL KK JJ I
NNNN MMM LL KK JJ I
NNN MMM LL KK JJ I
           MM NNN 00000
MM NNN 000
 JJ KK LL
                                            00000
         NNNN 000000
LL MMM NNNN 00000
       LL
                                         000000
 JJ KK LL
                       LL MMMM NNNN
                                                         LL
                                              NNNN MMM
  000000000000000
                                                    MMM
                                                              KK JJ
                                            NNNN
                                                        LL
                                                       LL
                      NNNNNNNN
                                       NNNNNNNN
                                                  MMM
                                                     LLL KKKK JJ II
LLLL KKK JJ II
LLLL KKK JJ II
LLLL KKK JJ II
                                                MMMM
                        NNNNNNNNNNNNNNNNNNNN
   JJ KKK FFFF
JJJ KKK FFFF
JJ KK FFFF
                            NNNNNNNNNNNNN
                                              MMMMM
                                            MMMMMM
                                                     LLLL
                                                   LLLL
                    MMMMMMM
                                          MMMMMMM
II
             LLLL
H
    JJ
        KKKK LLLL
                      MMMMMMMM
                                       MMMMMMMM
                                                  LLLL
II
    111
         KKK
              LLLLL
                        LLLLL
                                                         KKK
                                                              111
    111
         KKK
                          MMMMMMMMMMMMMMMMMM
               LLLLL
                                                LLLLL
    111
         KKKK
                LLLLL
                           MMMMMMMMMMMMMMMM
                                                        KKKK
                                                 LLLLL
                                                              JJJ
                            MMMMMMMMMMMM
   111
         KKKK
                LLLLLL
                                               LLLLLL
                                                        KKKK
  1111
        KKKK
                LLLLLL
                             MMMMMMMMMM
                                                LLLLLL
                                                         KKKK
  JJJJ KKKKK
                              MMMMMMMMMM
                                                         KKKKK
               LLLLLL
                                               LLLLLL
 111
       KKKKK
               LLLLLL
                            MMMMMMMMMMMMM
                                                          KKKKK
                                                LLLLLL
     KKKK
1111
            LLLLLL
                          MMMMMMMMMMMMMMMMM
                                                 LLLLLL
                                                           KKKK
    KKKK LLL
            LLLLLL
                        MMMMMMMMMMMMMMMMMMMMMM
                                                    LLLLLL
                                                            KKKK
KKKK LLLLLL MMMMMMM
                    LLLLLL
                 MMMMMMMMMMM
                                         MMMMMMMMMMM
                                                        LLLLLL
   LLLLLL MMMMMMMM
                 MMMMMMM
                                                          MMMMMMM
   M NNNNNNN NNNNNNNN
                  00000000000
                                                   000000000000
           000000
                                                                 000000
                                                            PPPPPPPPPPP
00000000000
 000000000000000000
```

Figure 29. Z configuration, θ_1 = 45°, RBT = -0.392 (-0.392), ΔL = 0, $\Delta \theta_2$ = 0.007 rad.

```
CCCCCCCCCCC
                                                          ccccccccccc
       DODDDDDDDDDDD
                                                        DDDDDDDDDDDDD
        EEEEEEEEEE
                                                        EEEEEEEEEE
GG
        FFFFFFFFF
                                                                         GG
HH
       GGGGGGGG
                               FFFFFFFFFFFF
                                                           GGGGGGGG
                                                                         HH
      нниннин
                      IIIIIII
                 нинининининини
                                         ннинининининини
                                                                IIIIIII
  111111
             IIIIIIIII
                                                   111111111
                         KKKKK
                  111111111111
   LLLLL
                             11111111111111111
                   KKKKKKKKKKK
                                             KKKKKKKKKKKK
                                                             LLLLL
           LLLLLL
                            KKKKKKKKKKKKKKKKKK
                                                                 MMMM
        MMMMM
                                                              MMMMM
 NNNN
00
    NNNN MMMMMM
                      MMMMMM NNNN
                                                    MMMMMMM NNNN 000
       NNNN
 000
              MMMMMMM
                             LLLLLLLLLLLL
   000
        NNNN
                  MMMMMMMM
                                                MMMMMMMM
      0000
            NNNNN
                      ммммммммм
                                          MMMMMMMMMM
                                                         NNNNN 0000
                                                                       PPP
  PPP
       0000
              NNNNN
                        MMMMMMMMMMMMMMMMMMMMMMMMM
                                                       NNNNN
                                                               0000
                                                                     PPP
        0000
               NNNNNN
   PPP
                             мммммммммммммммм
                                                     NNNNN
                                                              0000
    PPP
          0000
                                 MMMMMMMM
                                                            0000
                 NNNNNN
                                                   NNNNNN
      PPP
 000
            0000
                    NNNNNN
                                                 NNNNNN
                                                           0000
                                                                PPP
                                                                      000
 999
       PPP
             0000
                     NNNNNNN
                                               NNNNNNN
                                                                PPP
                                                          0000
                                                                      000
   999
        PPP
              0000
                      NNNNNNN
                                              NNNNNN
                                                         0000
                                                               PPP
                                                                    QQQ RR
   666
        PPP
              0000
                      NNNNNN
                                              NNNNNNN
                                                        0000
                                                               PPP
                                                                   000
     99
         PPP
              0000
                      NNNNNNN
                                              NNNNNNN
                                                        0000
                                                              PPP
                                                                    QQ
 RR
     000
         PPP
               000
                       NNNNNNN
                                              NNNNNN
                                                        000
                                                              PPP
                                                                   QQQ RR
     QQ
          PPP
               0000
                      NNNNNNN
                                              NNNNNNN
                                                       0000
                                                              PPP
                                                                   9.0
                                                                       RR
 RR
     99
          PPP
               0000
                       NNNNNN
                                               NNNNNN
                                                       0000
                                                              PPP
                                                                   90
                                                                     RR
  RR
      999
          PPP
               000
                      NNNNN
                                                NNNNN
                                                              PPP
                                                                  000
  RR
      000
          PPP
               000
                      NNNNN
                                                NNNNN
                                                        000
                                                              PPP
                                                                  QQQ RR
                                                                  QQ RR SS
   RR
      QQ
          PPP
               000
                      NNNN
                                 MMMMMMMM
                                                 NNNN
                                                              PPP
                                                        000
SS
   RR
      QQ
          PPP
              000
                     NNNNN
                                мммммммммм
                                                 NNNNN
                                                         000
                                                              PPP
                                                                  QQ
                                                                      RR
   RR
       99
          PP
              000
                     NNNN
                              MMMMMMMMMMMMMMM
                                                  NNNN
                                                         000
                                                              PP
                                                                  00
                                                                      RR
S
   RR
      QQ
          PP
              000
                    NNNN
                            MMMMMMMMMMMMMMMMMMM
                                                   NNNN
                                                         000
                                                               PP
                                                                  QQ
                                                                      RR
   RR
       QQ
          PP
              00
                   NNNN
                           MMMMMMMMMMMMMMMMMMMMMMMMM
                                                    NNNN
                                                          00
                                                               PP
                                                                  00
                                                                      RR
                                                                     RR SS
SS
   RR
      QQ
          PP
              000
                   NNN
                          MMMMMMM
                                          MMMMMMM
                                                     NNN
                                                          000
                                                              PP
                                                                  QQ
SS RR
       QQ
          PP
              000
                  NNNN
                         MMMMMM
                                            MMMMMM
                                                     NNNN
                                                          000
                                                              PP
                                                                  QQ
                                                                      RR SS
SS RR
       QQ
          PP
              00
                  NNN
                        MMMMM
                                              MMMMM
                                                      NNN
                                                           00
                                                              PP
                                                                  00
                                                                      RR
                       MMMMM
SS RR
       QQ PP
              00
                  NNN
                                               -
                                                      NNN
                                                           00
                                                               PP QQ
    R
      QQ PP
              00
                 NNN
                       MMMM
                                               MMMM
                                                       NNN
                                                           00
                                                               PP
                                                                  QQ
                                  LLLLLL
       QQ PP
             000
                 NNN
                      MMMM
                                                MMMM
                                                       NNN
                                                               PP QQ
                               LLLLLLLLLLLL
                                                           000
    R
      QQ PP
             000
                 NNN
                      MMM
                                                 MMM
                                                           000
                                                               PP
                                                                  QQ
                               LLLLLLLLLLLLLL
                                                       NNN
T SS RR QQ
         P
             00
                      MMMM
                              MMMM
                                                            00
                                                               P
                                                                  QQ RR SS
T SS
    RR QQ
          P
             00
                 NN
                      MMMM
                                                 MMMM
                                                       NN
                                                               P
                             00
    R
       Q
          PP 00
                      MMM
                             MMM
                                                            00 PP
     R
       Q
          PP
              00
                 NN
                      MMM
                             -
                                                        NN
                                                           00
                                                              PP
   S
     RR GG
          PP
              00
                      MMM
                                                  MMM
                                                              PP QQ RR S
                             LLLLLLLLLLLLLLLLLLL
                                                           00
TT S R QQ
          P
              00
                 NNN
                      MMMM
                                                 MMMM
                                                      NNN
                                                           00
                                                              P
                                                                 QQ R S TT
                             PP
UTSSR
        Q
              0
                  NN
                                                 MMM
                                                           0 PP
                             R QQ
           P
              00
                  NN
                       MMM
                                                 MMM
                                                          00
                                                              P QQ R
```

Figure 30. Z configuration, θ_1 = 45°, RBT = 0 (-0.348), ΔL = 0, $\Delta \theta_2$ = -0.007 rad.

```
GGGGGGGGGGGGGGG
                                                     ececececececece
         нининининини
                                                         нининининини
       IIIIIIIIII
                                                              11111111111
    11111111
                        TITITITI
                 11111111111111111
  KKKKKKK
                                             1111111111111111
                                                                      KKKKKKK
LILLL NO.
                                                         KKKKKKKKKK
                                                                         LLLLL
 KKKKKKKKKKKKKKKKKKKKKKKKKKKKKKK
                                                                LLLLLLL
                                                      LLLLLLLLL
                                              LLLLLLLL MMMMMMM NNNNN OMMMMMMMM NNNNN OOOO
 0000
                                                                          0000
                                                                NN 0000 PPF 00000 PPPP 0 00000 PPPP 0 0000
   PPP 0000 NAMANAN
 NNNNNNN OOUU-
NNNNNNNN OOOOO PPP
PPP
            00000 NNNNNNNNNN
                                            NNNNNNNNNN
 000
                       NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                       00000
                            NNNNNNNNNNNNNNNNNNNNNNN
                                                                   PPPP
                                                                         0000
                             NNNNNNNNNNNNNNNNNNN
                                                       000000
                                                                  PPPP
                                                                         999
                               NNNNNNNNNNNNNNNNN
                                                                 PPPP
                                                                       000
                                                        00000
                               NNNNNNNNNNNNNNNNN
                                                                PPPP
 RR
          PPPP
                  000000
    000
                                                       000000
                                                                      000
           PPP
                                                                PPP
 RRR
                               NNNNNNNNNNNNNNNNN
                                                                       QQQ RRR
     QQQ
                  00000
                                                       00000
           PPP
                  000000
                              NNNNNNNNNNNNNNNNNN
 RRR
     000
                                                                PPP
                                                                      000
                                                       000000
                                                                            RRR
           PPP
 RR
      999
                             NNNNNNNNNNNNNNNNNNNNNN
                                                                 PPP
                  00000
                                                        00000
                                                                      000
                                                                           RR
           PPP
  RR
      999
                  0000
                           NNNNNNNNNNNNNNNNNNNNNNNNN
                                                                 PPP
                                                         0000
                                                                      000
                                                                            RR
  RR
      QQ
          PPP
                 0000
                          NNNNNNNN
                                                                 PPP
                                           NNNNNNNN
                                                          0000
                                                                       00
                                                                            RR
  RR
      QQ
          PPP
                0000
                        NNNNNNN
                                               NNNNNNN
                                                           0000
                                                                 PPP
                                                                       00
                                                                            RR
  RR
     QQQ PPP
               0000
                      NNNNNN
                                                  NNNNNN
                                                            0000
                                                                  PPP
                                                                       000
                                                                            RR
  RR
         PPP
             000
                                 ммммммммммм
                                                                  PPP
     00
               000
                     NNNNN
                                                    NNNNN
                                                             000
                                                                       00
                                                                            RR
  RR
     QQ PPP
                   NNNNN
                              ---
                                                                  PPP
                                                      NNNNN
                                                              000
                                                                        00
                                                                          RR
             000
                                        MMMMMMMM
                                                              000
 RR QQQ PP
                   NNNN
                           MMMMMMMM
           OOO NNN MMMM
                                                        NNNN
                                                                   PP
                                                                        GGG RR
 RR
    QQ PP
                        MMMMMM
                                               MMMMMM
                                                         NNN
                                                                    PP QQ
                                                                000
                                                                000 PP QQ
                                                   MMMM
 RR QQ
  QQ PP 000 NNN MMMM LLL
QQ PP 000 NNN MMMM LLLLL
QQ PP 00 NNN MMM LLLL
QQ PP 00 NNN MMM LLLL
QQ P 00 NNN MMM LLLL
KKK
        PP 000
                       MMMM
                                  LLLLLLLL
                                                          NNN
                          LILLILL LILLILL MMMM
LILLILLI LILLILLI MMMM
LILLILLI LILLILLI MMM
                                                  MMM NNN 000
LLLL MMM NNN 00
                                                           NNN 000 PP QQ
                                              LLLL MMMM
                                                                      PP Q
                                                              NNN OO PP
                                                                          QQ R
MMM NNN 00 PP QQ
                                 KKKKKKKKKKKK
                           KKKKKK KKKKKKKKKKK LLLL
                                                KKKK LLLL MMM NN 00 PP QQ
KKKK LLL MMM NN 00 PP QQ
                                                           MMM NNN DO P
                                                  KKKK LLL
                                                             MM NN OO
                                                         LLL
                                                           iı
                                                            LL MM N OO PP QQ
LL MM NN O P Q
                                             11111
                                                      KKK
                                                1111
                                                                  MM NN OO PP
                                                         KK
                                                             LL
                                                              LL MM NN OO PP
                                                    1111
                                                         KK
                                                           KK LL MM N O
                                                      111
                                                      111
                                                           KK LL
                                                                   MM NN DO P G
                                                 IIII
                                                       JJJ KK LL
                                                       JJJ KK LL MM NN 00 P Q

JJ KK LL M N 00 P Q

JJ KK LL M N 00 P Q
                                                 IIII
                                                  IIII
                                                   III
                                                    III JJJ KK LL M
```

Figure 31. Z configuration, θ_1 = 45°, RBT = -0.348 (-0.348), ΔL = 0, $\Delta \theta_2$ = -0.007 rad.

```
NNN
     000
         PPPP
                999999
                              RRR
                                          999999
                                                  PPPP
                                                        000
                                                            NNN
NNN
     0000
          PPPP
                 0000000
                                        0000000
                                                  PPPP
                                                       0000
                                                            NNN
 NNN
     000
          PPPPP
                   999999999
                                     99999999
                                                PPPPP
                                                       000
                                                            NNN
 NNN
     0000
           PPPPP
                    PPPPP
                                                      0000
                                                            NNN
 NNNN
      0000
             PPPPPP
                       PPPPPP
                                                      0000
                                                           NNNN
  NNN
       0000
              PPPPPP
                                            PPPPP
                                                     0000
                                                           NNN
  NNNN
        00000
                PPPPPPP
                                         PPPPPPPP
                                                   00000
                                                          NNNN
  NNNN
         00000
                  PPPPPPPPPPP
                                   PPPPPPPPPPPP
                                                  00000
                                                         NNNN
   NNNN
          000000
                     000000
                                                         NNNN
   NNNNN
           0000000
                          PPPPPPPPPPPP
                                              0000000
                                                        NNNNN
MM
    NNNNNN
             000000000
                                           000000000
                                                      NNNNNN
                                                              MM
MM
     NNNNNN
               0000000000000
                                      000000000000
                                                     NNNNNN
                                                              MM
MMM
      NNNNNNN
                  NNNNNNN
                                                             MMM
MMMM
       NNNNNNN
                       00000000000000000000000
                                                  NNNNNNN
                                                            MMMM
MMMMM
        NNNNNNNNN
                                               NNNNNNNNN
                                                            MMMMM
MMMMM
          NNNNNNNNNN
                                            NNNNNNNNNN
                                                            MMMMM
MMMMMM
           NNNNNNNNNNNNNNN
                                      NNNNNNNNNNNNNNN
                                                           MMMMMM
MMMMMMM
              MMMMMMM
MMMMMMMM
                 MMMMMMMM
MMMMMMMM
                     NNNNNNNNNNNNNNNNNNNNNNNNNN
                                                         MMMMMMMM
MMMMMMMM
                                                         MMMMMMMM
MMMMMM
                                                           MMMMMM
NNNNNNNNNNNN
                                                     NNNNNNNNNNNN
NNNNNNNNNNNNNNNNNNNN
                                             NNNNNNNNNNNNNNNNNNNNNN
      0000000000
                     NNNNNNNNNNNNNNNNNNNNNNNNNNNN
                                                      0000000000
      0000000000
                                                0000000000
PPPPPP
           0000000000000000
                                       0000000000000000
                   PPPPPPPP
999999
          PPPPPPPPP
                                             PPPPPPPPP
     999999
                 969666
  RRRRR
          99999999
                                             999999999
                                                        RRRRR
 SSSS
                  RRRRRR
                                                          5555
              RRRRRRRR
TTTT
      SSSSS
                                          RRRRRRRR
                                                     SSSSS
                                                            TTTT
UUU
     TTTT
           SSSSSSS
                                              SSSSSSS
                                                             UUU
          TTTTTT
                                                TTTTTT
    UUUU
                    UUUU
                                                              VV
                  TTTTTTTTT
   VVVV
         UUUUU
                                      TTTTTTTTT
                                                  UUUUU
                                                         VVVV
                                                              WW
                                        UUUUUUUU
   -
         VVVV
                 UUUUUUUUU
                                                   VVVV
                                                         -
                                                              XX
    XXX
         -
                VVVVVVV
                                         VVVVVVV
                                                  -
                                                         XXX
                                                             YYY
     Y Y Y
          XXXX
                 ---
                                         ---
                                                  XXXX
                 XXXXXXX
                                       XXXXXXX
                   ****
                                     YYYYYYYY
```

00000

PPPP

000

NNN

NNN

000

PPPP

99999

Figure 32. Z configuration θ_1 = 45°, RBT = 0 (-0.393), ΔL = 1.0 cm, $\Delta \theta_2$ = 0.00428 rad. The curvature along the x-coordinate has been reduced to approximately zero.

```
SSS TTT UUUU VVVVVV
                     VVVVVV UUUU TTT
 SSS TIT UUUU
SSS
 SSS TITITITI VVVVVVV VVVVVVVV UUUUU TTTT
 SS
RRR
555
GGGG
                               0000
 PP QQQQQ
                             00000 PP
                         RRRRRR
                            QQQQQ F.
                       RRRRRRRR
  GGGGGG PPPPP
                        0000000
      99999999999
                    00000000000
                            PPPPPP
    PPPPPPPP
                          PPPPPPP
000
                       PPPPPPPPP
000000
                              000000
       00000000
                             00000000
  0000000000
            0000000000
                       000000000000000
    000000000000000
      NNNN
                               NNNN
NNNNNNNNN
             00000000000000000
                             NNNNNNNNN
NNNNNNNNNNNNNNNN
                         NNNNNNNNNNNNNNNNN
```

```
NN
NNNNN
           NNNNN
            NNNNNNNN
                                           NNNNNNNN
              ММММММММММММММММММММММММММММММММММ
 NNNNNNNN
                                         NNNNNNNN
                 MMMMMMMMMMMMMMMMMMMMM
   NNNNNNNN
                                       NNNNNNNN
0000
     NNNNNNNNN
                                    NNNNNNNN
  NNNNNNNNN
000000
                                           000000
PPPP 000000
                          NNNNNNNNNNNNNN
                                         000000
   0000000
                                 OCOOOOOO PPPPP
O PPPPP QQQQ
PPPPPPPP QQQQ RR
P QQQQQ RRRR
 2000
             RRRR
                                      RRRR
              RRRR
                               00000000
  SSS
                                           SSS
    $$$$
 TTT
          RRRRRR
                  9999999999999999
                                  RRRRRR
                                            TTT
         SSSSS
               RRRRRRRRRRRRRRRRRRRRRRRRRRR
                                         TTTT
 UUU
                                    55555
                                             UUU
 VVV UUU
                                         UUU VVV
        TTTTT
              SSSSSSSS
                            SSSSSSSSS
                                     TTTTT
        UUUU
              TTTTTTT
                                     UUUU
                              TTTTTTT
                                     VVVV
  XX WWW VVVV
             UUUUUUUU
                              UUUUUUUU
                                         WWW
                                            XXX
 XXX
                              VVVVVV
             V V V V V V V
                                     -
        -
                                        XXX
                            -----
         XXXX
      YYY
               -----
                                   XXXX
                ******
           YYYY
```

Figure 33. Z configuration, θ_1 = 45°, RBT = -0.393 (-0.393), ΔL = 1.0 cm, $\Delta \theta_2$ = 0.00428 rad. The curvature along the x-coordinate has been reduced to approximately zero.

LLL 1111111 LLLLLL KKKKKKKKKKKKKKK MMMM 000 NNN LLLLLL LLLLLL 000 000 NNN MMMMM LLLLLLLLLLL LLLLLLLLLLL MMMMM 000 PP 000 NNNN MMMMM NNNN 000 PP 000 NNNN MMMMM MMMMM NNNN 000 PP 000 PP 000 NNNN MMMMMMM MMMMMMM NNNN 000 NNNN QQQ PPP NNNN MMMMMMMM MMMMMMMM 000 NNNN 99 000 **ММММММММММММММММММММММММ** NNNN QQ 000 RR QQ 0000 NNNNN MMMMMMMMMMMMMMMMMM NNNNN 0000 PPP 000 PPP NNNNN MMMMMMMMMMMMM NNNNN 000 PPP 000 NNNNN MMMMMMMM NNNNN 000 PPP QQ 0000 NNNNN NNNNN 0000 PP QQ RR RR QQ PP 0000 NNNNN NNNNN 0000 PP QQ RR PPP QQ RR SS QQ PPP SS RR 000 NNNNNN NNNNNN 000 RR QQ PP 0000 NNNNNN NNNNNN 0000 RR QQ PPP QQ RR SS PP QQ RR S T SS PPP 000 NNNNN NNNNN 000 PP S 0000 NNNNNN NNNNNN 0000 PPP QQ RR SS TT TT SS RR QQ PPP 000 NNNNNN NNNNNN 000 PP RR QQ 000 NNNNNN NNNNNN 000 PP TT SS RR QQ T S RR QQ PP PP QQ RR SS TT 00 0000 NNNNN NNNNN 0000 PPP PPP 000 NNNNNN NNNNNN 000 QQ RR SS RR PP PP QQ 000 NNNNNN NNNNNN 000 QQ RR SS T U PP QQ RR S TT U U TT S RR QQ PP 000 NNNNNN NNNNNN 000 PPP SS RR 99 000 NNNNNN NNNNNN 000 QQ R SS TT U U TT SS R PP QQ PP 000 NNNNN NNNNN 000 000 PP QQ RR S T U T S RR QQ PP 000 NNNNNN NNNNNN PPP 000 NNNNNN NNNNNN V UU T S RR QQ PP V U TT SS R QQ PPP PP QQ RR S T UU V 000 000 NNNNNN NNNNNN 000 PP QQ R SS TT U V
000 PPP QQ R SS TT U V
000 PPP QQ R S T U VV
00 PPP QQ R S T U V W
00 PPP QQ RR S T U V W
00 PPP QQ RR S T U V W
PP QQ RR S T U V W
PP QQQ RR S T U V W PPP 000 NNNNNNN NNNNNNN 000 000 V UU T RR QQ PP R QQ PPP SRR NNNNNNNN NNNNNNNN S VV U 000 NNNNNNNNNNNNNNN 000 U TT SS RR QQ PPP 0000
UU T S RR QQ PP 0000
VU T S RR QQQ PP 0000
VV U T SS R QQQ PPP 0000
V U TT SS R QQQ PPP 0000 0000 NNNNNNNNNNNNN OO PP QQ RR S TUUV WW
O PP QQQ RR S T U V W
PPP QQQ R SS T U VV W X
PPP QQQ R SS TT U V W X V UU T NNNNNNNNNNN 0000 V U T NNNNN 0000 w vv u 0000 X W V U TT SS R QQQ PPP 000000 X W V U TT SS RR QQ PPPP 0000 000000 PPPP QQ RR SS TT U V QQ RR SSTTU V W XX Y Q RR S T U V W XX Y RR SS T U VV W X Y Y XX W V PPPP U TT SS RR QQ Y XX W V U T S RR PPPPP QQQ RR S RR QQQ SS RR QQ Y X W VV UU TT S Y X WW V U T S S TT UU VV W X Y S T U V WW X Y RR Y X WW V U 99999 SS Y X W VV UU TT SS RRR 9999999999 RRR TT UU VV W X Y SS YY X WW V UU TT SS RRRRR RRRRRRRRRRR SS TT UU V WW X YY
Y XX W V UU TT SSS RRRRRRRRRRRRR SSS TT UU V W XX Y
Y X W V UU TT SSSSS SSSSS TT UU V W X Y

Figure 34. Z configuration, θ_1 = 45°, RBT = 0 (-0.361), ΔL = 1.0 cm, $\Delta \theta_2$ = -0.00580 rad. The curvature along the y-coordinate has been reduced to approximately zero.

NNNNNNN PPPP 0000 0000 NNNNNNN MMMMMMMMMMMMM 0000 PPPP NNNNNNNN 0000 000000 PPPP NNNNNNNN NNNNNNNNNNNNNNNNNNNNNNNNNNNNNN 000000 999 000000 NNNNNNNNNNNNNNN 000000 000 PPPPP 0000000 0000000 0000 PPPP 00000000 PPPP 00000000 0000 9999 PPPPP 00000000000000 0000000000000 PPPPP 999 PPPPP PPPPP 000 SS 000 PPPPP PPPPP 999 SS 0000000000000000000000 55 RRR PPPPP 0000000000000000000 PPPPP 999 QQQ PPPPP PPPPP 000 SS RRR 999 000000000000000000 55 SSS RRR 9999 PPPPP 000000000000000 PPPPP 0000 RRR SSS SS RRR PPPPP 000000000000000 PPPPP 999 RRR 000 SS RRR PPPPP PPPPP TT SSS 999 000000000000000000 999 RRR SSS PPPPP 0000000000000000000 PPPPP 999 RRR 999 RRR 55 SS PPPP PPPP RR SS RR 000 999 SS TT PPPP TT SS RR 999 PPPP 0000000000000000000000 999 RR 55 PPPP PPPP RR RR 0000000000 000000000 TT SS 999 999 SS TT SS RRR 000 PPPP 0000000 0000000 PPPP GQG RRR SS SS RRR 000 PPP 0000000 0000000 PPP 999 RRR 55 PPP 000000 PPP RR SS QQ 00 SS RR 000000 SS RR 999 PPP 00000 NNNNNNNN 00000 PPP RR 000 SS PPP RR QQ NNNNNNNNNNNNNNN 00 RR SS 0000 0000 R QQ PPP PPP 00 SS 0000 0000 PP PP S QQ NNNNNNN 0000 0000 NNNNNNN 00 QQ PPP RR S RR 000 NNNNNN NNNNNN 000 PPP 00 PP RR 000 NNNNN 000 S NNNNN 00 SS R QQ PPP MMMMMMMM NNNNN 000 PPP .. 000 NNNNN 55 SS RR QQ PP ммммммммммммм PP 00 NNNN NNNN 00 00 SS TT SS RR QQ PP 000 NNNN мммммммммммммммм NNNN 000 PP RR SS 00 Q PP 000 PP SS RR NNN MMMMMMM MMMMMMM NNN 000 Q RR SS SS RR QQ PP 00 MMMMM MMMMM PP QQ RR SS NNN NNN 00 PP MMMMM -PP SS RR QQ 00 00 NN NN QQ RR SS SS RR QQ PP MMMM OO NNN MMMM NNN 00 QQ RR SS T SS RR QQ T S RR QQ TT S R QQ P 00 MMMM LLLLLLLL MMMM 00 P QQ RR SS T NN NN MMMM -P 00 NN LLLLLLLLLL NN 00 GG RR 00 NN MMM LLLLLLLLLLLL MMM NN 00 GG R S P -P Q MMM NN 00 00 NN LLLLLLLLLLLLLLLLL R Q PP 00 MMM 00 PP MMM NN NN LLLLLLLLLLLLLL S RR QQ PP MMM MMM PP QQ RR S 00 NN NN 00 UT LLLLLLLLLLLLLLL P Q R S SRQ MMMM NNN 00 00 NNN MMMM LLLLLLLLLLLLLLL T S RR Q T S R Q 0 0 PP 0 PP NN MMM MMM NN LLLLLLLLLLLLL RQ P R U NNN MMMM LLLLLLLL MMMM NNN NN OO PP QQ RR S NN OO PP Q R SS NNN OO PP Q R SS T U TT S RR QQ PP 00 MMMM PP OO NNN MMMMMM Q PP OO NNN MMMMMMM Q PP OO NN V U T SS R Q PP TUVW Q R SS T U V V U T SS R Q MMMMMM V UU T S R NNN DO PP Q R S T UU V W OO PP Q R S T UU V W X MMMMMMMM NNN X W V UU T S R T UU V W X NNNN NNNNN NNNNN OO PP QQ R SS T UU V W X Y NNNNNNNNNNNNNNNNNN OO PP QQ RR SS T U V W X Y X W V U T SS R QQ PP 00 X W V U T SS RR QQ PP 0 X W V UU T SS R X W VUT S R QQ PP O 0000 PP QQ R S T U V 0000 NNN

Figure 35. Z configuration, θ_1 = 45°, RBT = -0.361 (-0.361), ΔL = 1.0 cm, $\Delta \theta_2$ = -0.00580 rad. The curvature along the y-coordinate has been reduced to approximately zero.

```
(X YYYYY
                        VVVVVV XXXX
                             -
    UUUUUU
 VVVV
                              VVVV
UUUUU
                           TTTTT
                               UUUUU
                          SSSSSSS
TTTT
                               TTTT
SSSSS
                       RMMn...
QQQQQQQQ
QQQQQQQ
QQQ
RRRRRR
   000
   000000000000
                       000000000000
 000000000
            NNNNNNNNNNNNNNNNNNNNN
                          0000000000
0000000
        0000000
    NNNNNNNNNNNNNNNNNNNNNNN
                     NNNNNNNNNNNNNNNNNNNNNN
NNNNNNNNNNNNNNNNNNN
                        NNNNNNNNNNNNNNNNNN
NNNNNNNNNNNNNN
                           NNNNNNNNNNNNN
NNNNN
                               NNNNN
*****
                             MMMMMMMM
ммммммммммммм
                          MMMMMMMMMMMMMM
 MMMMMMMMMMMMMMMMMM
                        MMMMMMMMMMMMMMMMMMM
   MMMMMMMMMMMMMMMMMM
                     ммммммммммммммммм
   KKKKK
                             LLLLLLLL
                          TTTTTTTT KKKKK
          KKKKKKK
                       TITTE KKKKKKK
11111
                       KKKKK 111111
                            IIIII
 111111
 ннннн
          IIIIII
    ннннн
 GGGG
         111111111111111 111111111111111
                         ннннн
                              6666
HHHHHHHHHHH
GGGGGGGGGG FFFFF EEEE
FFFFFFFF EEEEE DDDD CCCC BBB
                   нинининини
                          GGGGG
                              FFFF
DD
AAAAAAAAAAA BBBBP CCCCCCC
                    CCCCCCCC BBBBB AAAAAAAAAA
```

Figure 36. U configuration, θ_1 = 45°, RBT = 0 (1.102), $\Delta L = \Delta \theta_2 = 0$.

```
יייטטט טעטטט
X WWW VV UUU
       V V V V
                                          UUUUU
                                                  VVVV
         RRRRR
                                                       WWW
                                               TTTTT
                                        5555555
                                                      UUU
                                                           VV
    SSSS
                  RRRRR
                                                    5555
  RRRR
       00000
              PPPPPP
                                              00000
9999
     PPPPP
            000000
                        NNNNNNNNNNNNNNN
                                           000000
                                                   PPPPP
                                                         0000
     0000
           NNNNNNN
                       МММММММММММММММММММММ
                                            NNNNNNN
                                                   0000
                                                          PPP
      and thitle
           MMMMMM
000
     NNNN
                       LLLLLLLLLLLLLLLLL
                                            MMMMMM
                                                    NNNN
                                                          000
    MMMMM
NNNN
                                                   MMMMM
      LLLLLLL
                                                         NNNN
MMMMM
                                 KKKKKKKKKKKKK
                                                 LLLLL
                                                        M M M M M
   LLLLL
                                                     LLLLL
LLLLL
                                                 KKKKKK
                                                         LLLLL
                                                   KKKKKK
   KKKKKK
             11111111111
                                                      KKKKK L
                                       TITITITI
  KKKKK
          1111111111
                                          1111111111
KKKKKK
         1111111111
                                            1111111111
                                                       KKKKKK
KKKKK
         1111111111
                                            TITITITI
                                                         KKKKK
KKKKK
         111111111111
                                          44444444444
                                                         KKKKK
KKKKKK
           111111111111111
                                      KKKKKK
KKKKKKKKK
              KKKKKKKKK
 KKKKKKKKKKKK
                         1111111111111
                                                  KKKKKKKKKKK
     KKKKKKKKKKKKKKKK
                                          KKKKKKKKKKKKKKKK
              LLLLLLLLLLLLLL
                                                  LLLLLLLLLLLLLLL
      \\
                                                        NNNNNN
        00000000000000000
                                                 0000000000000000
               00000
                                                         00000
       PPPPPPPPPPPPPPP
                                          PPPPPPPPPPPPPPP
   PPPPPPPPP
                         0000000000000
                                                 PPPPPPPPPP
               PPPPPPPP
 PPPPPP
            000000000000000
                                                      PPPPP
                                     909090909090999
 PPPPPP
          00000000000
                                                       PPPPPP
                                          9099999999
 PPPPP
         000000000
                                            000000000
                                                      PPPPPP
  PPPPP
          GGGGGGGG
                                           0000000000
                                                      PPPPP
   PPPPP
                                                 PPPPP 0
           000000000
                                          000000000
        PPPPPP
     PPPPPP
                                       0000000000
  00000
                 PPPPPP
                                                      00000
                                        PPPPPPP 0000 NNNN
PPPPP 00000 NNNN MM
000000 NNNN MMMM
NNNN 0000
           PPPPPP
        000000
                    00000000000000000
   NNNN
                                   PPPPPPPPPP
               PPPPPPPPPP
  MMMM
                                                      MMMM
       NNNN
       MMM
  LLL
                      NNNNN
                                                JJJJ III HHH
KKK JJJ II
FLF KKK J
WWW FFF
                                                  MMM
      LLL
            MMMMM
                     NNNNNNNNNNNNNNNNNNNNN
                                            MMMMM
 KKK
                    ******
   111
             LLLLL
                                           LLLLL
       KKK
                                                          11
HHH III JJJJ KKKKK LLLLLLLLLLLLL KKKKK JJJJ III HHH

FF GGG HHH IIII JJJJJJ JJJJJJ JJJJJJ III HHH

D EE FFF GGG HHHHH IIIIIIIIIIIIIIIII HHHHHH GGG FFF FE D

CCC DDD EEEE FFFF GGGGGGGGGG GGGGGGGG FFFF FE D
```

```
Figure 37. U configuration, \theta_1 = 45°, RBT = 1.102 (1.10), \Delta L = \Delta \theta_2 = 0.
```

```
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
                                                                                       MMMMMMMMM LLLLLL
                                                                                                      ммммммммм
                                 мммммммммм
                                                                                                                       мммммммммммммммммм
 NNNNNNNN
                NNNNNNNNNNN
                                                                                                                    NNNNNNNN OOOOO
00000 NNNNNNNNN
PPP 00000 NNNNNNNNN
QQ PPPP 0000 NNNNNNNNN
R QQ PPPP 00000 NNNNNNNN
                                                                                                    NNNNNNNNN 00000

        QQ
        PPPP
        0000
        NNNNNNNNN
        NNNNNNNNNNNNNNN
        00000
        PPPP
        QQ
        RPPP
        QQ
        RPPP
        QQ
        RPPP
        QQ
        RPPP
        QQ
        RPPP
        QQ
        RR
        SS
        T
        T
        SS
        RR
        QQQ
        PPPP
        QQ
        QQ
        PPPP
        QQ
        QR
        RS
        T
        U
        V
        UU
        T
        SS
        RR
        QQQ
        PPPP
        QQ
        QQ
        QQ
        RR
        SS
        T
        UU
        V
        V
        UU
        T
        SS
        RR
        QQQ
        PPPP
        QQ
        QQ
        QQ
        RR
        SS
        T
        UU
        V
        W
        V
        UU
        V
        W
        V
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
        W
                                                                     ****
```

Figure 38. Z configuration, $\theta_1 = 70^{\circ}$, RBT = 0 (-1.997).

```
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
                                           CCCC BBB AAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAAA BBB CCCC
                                 0000000
AAAAAAAAAAAA B CC DDD EEEE
AAAAAAAAAAA B CC DD EE FF GGGG
AAAAAAA B CC DD EE FF GG HHH
                                          FFFFF
                          GGGGG
                       HHH IIIIIIIIIIIII
                                         JJJJJ III HH GG FF EE DD CC H AAAAAAA
JJJJJ III HH GG FF EE D C R AAA
KKK JJ II HH G F ED C R
LLLL KKK JJ II H G F FE D
MMMMMM LLL KK JJ II HH GG FF F
NNNNNN MMM LL KK JJ I H G
DOO NNNN MMM LL KK JJ I H H
AAA B C D EE FF GG HH III JJJJJ
B C D E F G HH II JJ KKK
   DE F G HH II JJ
DEEF G H II JJ KK LLLL MMMMM
EFF G H II JJ KK LLL MMMMM
G H I JJ KK LL MMM NNNNN NNNI
HH I JJ KK LL MMM NNNN 00000000000000
                       LLLL
   JJ KK LL MMM NNNN
                                          000000 NNNN MMM LL KK JJ II
                         000000
                                             00000 NNN MMM
 JJ KK
       LL
           MMM NNN
                     00000
                                  PPPPP
                                                      NNN MM LL KK J
         MM
                    0000
  KK LLL
                             0000
                                                        NNN MM
        MM NNN
                   0000
                           РРРРРРРРРРРРРРРРР
   LL
                                                  0000
 LLL MMM NNNN
                          РРРРРРРРРРРРРРРРРРР
                  0000
                                                          NNNN MMM LLL
                                                   0000
         NNNN
                 00000
                           РРРРРРРРРРРРРРРРРР
                                                           NNNN
                                                   00000
                                                                       1.1
        NNNNN
                000000
                            РРРРРРРРРРРРРРР
                                                            NNNNN
                                                   000000
       NNNNN
                 0000000
                                                  0000000
                                                                     MMMM
                                                             NNNNN
      NNNNNN
                  00000000000
                                             00000000000
                                                              NNNNNN
  NNNNNNNNN
                     NNNNNNNNN
NNNNNNNNNNNNN
                                                             NNNNNNNNNNNN
                                  00000
 NNNNNNNNNNNNNNNNNN
                                                      NNNNNNNNNNNNNNNNN
       NNNNNNNNNNNNN
                                                   NNNNNNNNNNNNN
                                                        NNNNNNN
                                                                     0000
         NNNNNNN
                      0000
         NNNNNN
                                                          NNNNNN
                                                                   0000
PP
         NNNNN
                   MMMMMMMMM
   000
                                             MMMMMMMMM
                                                                  000
                                                          NNNN OO
                                                          NNNNN
 PP 000
 PP 000 NNNN
PP 00 NNNN
QQ PP 000 NNN
                   MMMMMM
                                                 MMMMMM
                                                                000
                                                                     PP
QQ PP
                   MMMMM
                                                  -
                                                                   PP Q0
                             LLLLLLLLLLLLLLLL
                                                         NNNN
                                                         NNN 000 PP GQ
                   MMMMM
                            LLLLLLLLLLLLLLLLLL
                                                  MMMMM
RR QQ PP CO NNN
                   MMMM
                                                        NNN
                                                            OO PP QQ RR
                            LLLLLLLLLLLLLLLLLL
S R Q PP 00 NN
                    MMMM
                                                              PP Q
                                                      NN
                                                           00
                            LLLLLLLLLLLLLLL
 SS R QQ PP 00
                 NNN MMMM
                                                   NNN
                                                        OO PP QQ R SS T
                               LLLLLLL
    S RR QQ PP CO NNN MMMMM
                                                  NNN OO PP QQ RP S T U
 VV U T SS RR QQ P OO NNN MMMMMMMMMMMMM
                                                       P QQ RR SS T U VV
                                             NNN OO
X W V UU T SS RR QQ PP 000 NNNNN
Y X W V UU T SS RR QQ PP 0000
X W V U TT SS RR QQQ PPPP 000
                                                000 PP GG RR SS T UU V W X
                                          NNNNN
                                          0000 PP QQ RR SS T UU V W X Y
                                000
                                            PPPP QQQ RR SS TT U V W X
       Y X W V U TT S RRR
                          000
                                           QQQ RRR S TT U V W X Y
          SS T UU VV W X Y
             Y X W V UU TTTT
Y X WW VVV
                                        TTTT UU V W X Y
                                  UUUUU
                        XXX YY
```

Figure 39. Z configuration, $\theta_1 = 70^{\circ}$, RBT = -0.799 (-1.997).

```
AAAAAAAAAAAAAAAAAAA B C D E FFF
                                                                        GGGGG
                                                                                           FFF E
                                                                                                            D C B AAAAAAAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAAAAAA B C D E FF GG HHHH
AAAAAAAAAAAAAAAAAAB C D E F GG HH III
                                                                                                 GG FF E D C B AAAAAAAAAAAAAAAAA
                                                                                      нини
                                                                                         III HH GG F E D C BAAAAAAAAAAAAAAA
AAAAAAAAAAAAAAA C E F G H I JJJ AAAAAAAAAAAAAAA C E F G H I J KKK
                                                                                             AAAAAAAAAA BC DE F G H II J KK LLL
                                                                                            LLL KK JIIH GFED CBAAAAAAAAAA
MM LL K JIIH GFE DC BAAAAAAAAA
MMM L K JIH GF D BAAAAAAAA
AAAAAAAAAAA BC DE F G H II J K LL MAAAAAAAA BC DE F G H I J K L MM NN AAAAAA BC DE F G H I J K L MM NN AAAAA BC DE F G H I J K L MM NN AAAAA BC DE F G H I J K L M NN AAAA BC D F G H I J K L M NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L MM NN OO AAAAA BC D F G H I J K L MM NN OO AAAA BC D F G H I J K L M NN OO AAAAA BC D F G H I J K L M NN OO AAAAA BC D F G H I J K L M NN OO AAAA BC D F G H I J K L M NN OO AAAAA BC D F G H I J K L M NN OO AAAAAAA BC D F G H I J K L M NN OO AAAAA BC D F G H I J K L M NN OO AAAAA BC D F G H I J K L M NN OO
                                                           LL MMMM MMI
                                                                                     MMMM
                                                                                      NNNN MM L K J I H G F ED CR AAAAAAA
                                                                 NNNN
                                                                                             NNN MM L K J II G F ED CB AAAAAA
                                                                        000000000
                                                                                                NNN M L K J I H G F ED CB AAAAA
                                                                   0000000000000
                                                                                                    NN MM
                                                                                                                  LKJIHGF
                                                                                                                                                D CB AAAA
AAA B D EF G H I J K LL MM NN
                                                                                                     NN MM LL K J I H G FE D B AAA
                                                                   000000000000000
                                                                                                     NN MM L K J I H G F E DC BAAA
NN MM L K JJ I H G F ED C AA
AAAB CD E F G H I J K L MM NN
                                                                   0000000000000000
AA CDEFGHIJJK
                                                 MM
                                                         NN
                                                                   0000000000000000
                                                                                                     NN MM LLK JIHGFEDCBANN MM LLKKJIIHGFEDCB
A BC D E F G H I J K LL MM
                                                                     0000000000000
                                                         NN
  B CD E F G H II J KK LL MM NNN
                                                                                                    NNN MM
                                                                         000000000
                                                                                                  NNN
                                                                                                            MM L KK J
BCDEFGHIJKK
                                          L MM
                                                           NNN
                                                                              000
                                                                                                                                     IHGFEDCB
                                                                                                           MM LL KK JJ I HH G F E D C
  CDEFGHHIJJKK
                                          LL
                                                            NNNN
                                                                                              NNNN
                                                                                                        MMM LL KK JJ I H G FF E D C
                                                    MMM
CDEFFGH I JJ KK LL
                                                              NNNNNN
                                                                                        NNNNNN
  DEE F G H II JJ KK
                                                                  NNNNNNNNNNNNN
                                                                                                        MMM
                                                                                                                   LL KK JJ II H G F FE D
                                          LL
DEE F GG H I JJ KK
                                                      MMMM
                                                                       NNNNNNNNNN
                                                                                                      MMMM
                                                                                                                 LLL KK JJ
                                                                                                                                             H GG F EE D
                                          LLL
EEF GG HH II JJ KK LLL
E FF GG HH II JJ KK LLL
F G HH II JJ KK LLL
                                                                                                                 LLL KK JJ II HH GG F EE
LLL KK JJ II HH GG FF F
                                                                             NNN
                                                          MMMM
                                                                                                  MMMM
                                                                                                                          KK JJ II HH
                                                                                                                 LLL
   G HH II JJ KKK LLL
                                                                                                MMMMMM
                                                                                                                  LLL KKK JJ
                                                                                                  MMMMMM
G HH II
                   JJ KKK
                                                                                                                   LLL
                                                                                                                              KKK
                                        LLL
                                                                                                     MMMMMM
H II
                       KKK
                                   LLL
                                                                                                                                   KKK
                                                                                                                                              JJ II
                                                                                                                       LLL
               KKK LLLL
                                                                     NNNNNNNNNNNN
       11
                                                                                                                              LLLL
                                                                                                                     MMMMM
     KKKK
                  LLLL
                                 MMMMM
                                                      NNNNNNNNNNNNNNNNNNNNNNNNNN
                                                                                                                                        LLLL
                                                                                                                                                      KKKK
                     MMMMM
                                        NNNNNNN
                                                                                                                                                      LLLL
    LLLL
                   NNNNNNN
                                               000000000000000
                                                                                      000000000000000
                                                                                                                                  NNNNNNN
         0000000000
                                                   0000000000
                                                  TTTTTTTT
      TTTTTTTT
   VVVVVV
                                      XXXXX
                                      ~~~~~~~~
                                                                                                            ****
                                         ****
```

Figure 40. Z configuration, $\theta_1 = 70^{\circ}$, RBT = 0 (-2.166), $\Delta\theta = +0.007$.

```
GG
       FFFFFFFFFF
                                               FFFFFFFFFF
                                                              66
     KKKKK IIIIIIII
                  II
     ннининн
                                                     нниннин
                                                              II
   1111
                                                         1111
                                               IIIIIIII
                                                      KKKKK LI
             1111111
                                           TITITI
LLL
                                                            LLL
        LLLL
               KKKKKKKK
                                           KKKKKKKK
                                                    LLLL
000
                                                          NNN 000
  NNN
               LLLLLL
        MMM
                            KKKKKKKKKK
                                           LLLLLL
                                                    MMM
PPP 000 NNNN
             MMMMM
                                              -
                      NNNN 000 PPP
                                                         PP
 QQ PP
      PP PP
        00
                  MMMMMM
            NNN
                                               NNN
                                                     00
                                                            00
   QQ
           00
              000 NNNNN
               NNNN
                       мммммммммммммммммммм
                                             NNNN
                                                  00
                                                      PP
                                                          00
            000
                                                    PP
   R QQ
                           MMMMMMMMMM
                                               000
                                                       QQ R
SS
                                          NNNNN
                                                             SS
  S RR QQ PP
                                                   PP QQ RR
                    NNNNN
                                        NNNNN
                                              000
                                             000 PPP QQ R
000 PP QQ RR S
   S
      R
        QQ PPP
               000
                     NNNNN
                                      NNNNN
  TT SS RR QQ PP
                000
                     NNNNNN
                                     NNNNNN
                                            000
                                                      RR SS TT U
 U TT SS RR Q PPP 000
                      NNNNN
                                     NNNNN
                                            000
                                               PPP G RR SS TT U V
    T SS RR QQ PP 000
                                      NNNNN
                                                PP QQ RR SS T U V W
 V U
                     NNNNN
                                            000
   UTTS
                                                PP Q R S TT U V W
        R Q PP 000
                     NNNN
                                       NNNN
                                            000
 W V U T SS R QQ PP
                            ммммммммм
                 000 NNNN
                                       NNNN 000
                                                PP QQ
                                                     RSSTUVWX
      T S RR QQ PP 00
                          MMMMMMMMMMMM
                                                PP QQ RR S T U V X
                    NNN
                                            00
                                            00
   V U T S R QQ PP
                 OO NNN
                        MMMMM
                                   MMMMM
                                        NNN
                                                PP QQ R
                                                       STUVWXY
                                      MMM NNN OO PP QQ R S
                                    MMMM
   W V U T S R QQ PP OO NNN
                       MMMM
 YX VUTSR Q PP 00
                   NN
                      MMM
                                                   RSTUV
                              LLLLL
                   NN MMM
       T S R Q PP 00
                           LLLLLLLLLLL
                                       MMM
                                              OO PP Q R S T
  YX WV U T S R Q P OO
                   N
                      MM
                           LLLLLLLLLLLL
                                       MM
                                           N
                                              OO P Q R S T U VW XY
     V U S R
             Q P O
                   N MMM
                          LLLLLLLLLLLLLL
                                       MMM N
                                              OPRRS
   Y XW VU T S R Q PP O
                   NN MM
                                       MM NN
                                              OPPCRS
                          LLLLLL
                                LLLLLL
     W UTSRGPOONN MM
W UTSRG POONN MM
                          LLLLLLLLLLL MM NN OO P Q R S T U W
                                       MM NN OOP QR ST U W
                           LLLLLLLLLLLLL
         U TS R Q P OO NN MMM
                                     MMM NN OOP QR ST U
                            LLLLLLL
          UT
             R Q P OO NN MMM
                                    MMM NN OOPQ R TU
        XW VU T S R Q PP 00 NN
        XW VU T S R Q PP 00 NNN
YX WV U TS RR Q PP 00
                          MMMMMMMMMM NN OO PP Q R S T UV WX
                              NNN 00 PP Q RR ST U VW XY
00 P Q RR S TU V X
                         NNN
                                    OO P Q RR S TU V PPP Q R S T U V WX
            XW V U T S R
                      Q PPP
                              00000
                                   QQQ RRS TUV
               V U T
                     S RR QQQ
                     T S RRRR
                                 RRRR S T U V W Y
                WVU
                                   TT UU V W X Y
                Y X W V UU TT
                             SSSSS
                  Y XX W VV
                            UUUUUUUUU
                                     XX YY
                            -
```

Figure 41. Z configuration, $\theta_1 = 70^{\circ}$, RBT = 0 (-1.837), $\Delta\theta = -0.007$.

```
LMNOP
    MN OP Q S T U VV W X YY
                                                      Q PO NM
I K M N O P Q R S TT UU VV WWW
G H J K L M N O P Q RR SS TTT U
                                  WWW VV UU TT S R Q P O N M K
UUUUU TTT SS RR Q P O N M L K J
                         UUUUU
 GHIJKLM NN O P QQ RRR
                         SSSSS
                                        RRR QQ P O NN M L K J I H G
 G H I J K L MM NN O PPP QQQQ
                               RRR
                                      QQQQ PPP O NN MM L K J I H G
                                            DO NN MM LL KK JJ I H G
NNN MMM LL K JJ II HH G
 G H I JJ KK LL MM NN 00
                       PPPPP
                                     PPPPP
                                          00
G HH II JJ K LL MMM NNN
                       00000
                                     00000
JJJJ KKK LLL
III JJJ KKK LLL
HH I JJ KKK LL
               MMM
                    NNNNN
                              000
                                       NNNNN MMM LL KKK JJ I HH
               MMMM
                                                  FILL KKK JJJ III
                      NNNNNNNNNNNNNNNNNNNNNN
                                            MMMM
                MMMMMM
                          NNNNNNNNNNNN
                                           MMMMMM
      LLLLL
KKKK
                MMMMMMMM
                                          MMMMMMMM
LLLLL
             MMMMMMMMMM
                                           MMMMMMMMMM
  ммммммммммммммм
                                                MMMMMMMMMMMMMMMMM
  NNNNNNNN
                                                      NNNNNNNN
   0000
0000
0000
                                                    0000 PPP
                                             NNNNNNNNNN
          NNNNNNNNNN
NNNNNNNN
                                           NNNNNNN
```

Figure 42. U configuration, $\theta_1 = 70^{\circ}$, RBT = 0 (3.698), $\Delta L = \Delta \theta_2 = 0$.

```
P ST XY
                             YX TS P
LM GRS
                             SRQ ML
KLMN
    UVW
                              NMLK
                          WVU
HIJKLMNO
    RST
                       Y X V TSR
                            ONMLKJIH
         KKKKKKKKKKKK
                          KKKKKKKKKKKK
             MMMMMMMMMMMMMM
RR QQQ PRO-
 NNNNNNNN
                           NNNNNNNN
                         0000000
             NNNNNNNNNNNN
                             PPPP
                         PPPPPP QQQ RR
QQQQ RRR SS TT
RRR SSS TT U
R SS TT UU V W
          0000
        PPPPPPP
 TT SSS RRR QQQQQ
V UU TT SS RRR QQQQQ
                     00000
                    QQQQQ RRR
```

Figure 43. U configuration, θ_1 = 70°, RBT = 1.48 (3.698), $\Delta L = \Delta \theta_2 = 0$.

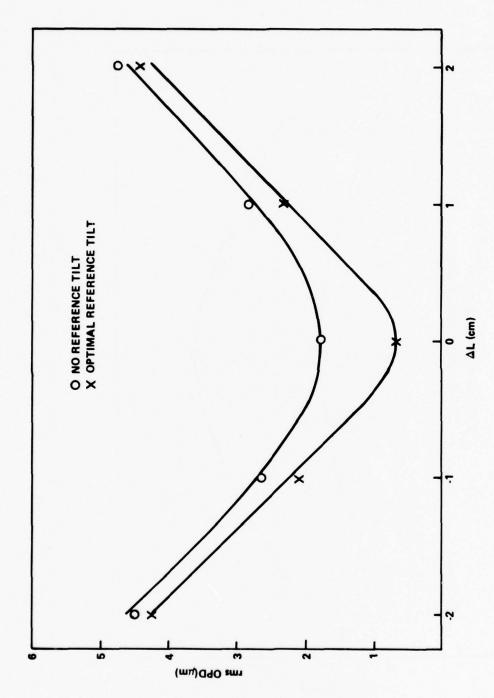


Figure 44. Predicted values (smooth curves) and calculated values of the root-mean-square OPD in microns as a function of ΔL , for Z configuration, θ_1 = 45°, $\Delta \theta_2$ = 0.

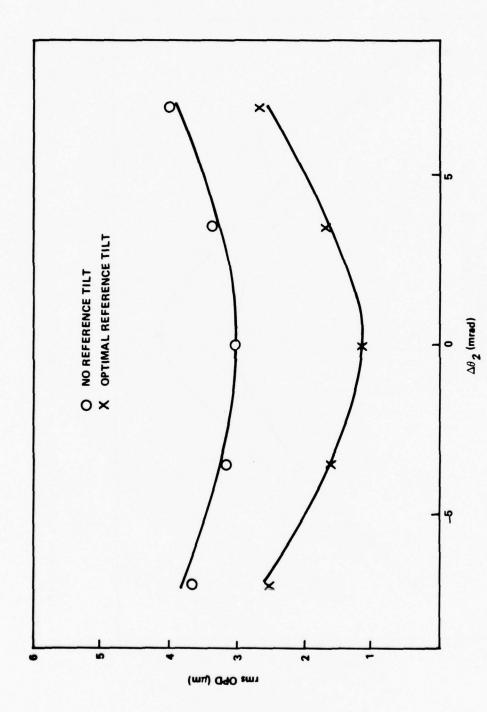


Figure 45. Predicted values (smooth curves) and calculated values of the root-mean-square OPD in microns as a function of $\Delta\theta_2$, for Z configuration, θ_1 = 55°, ΔL = 0.

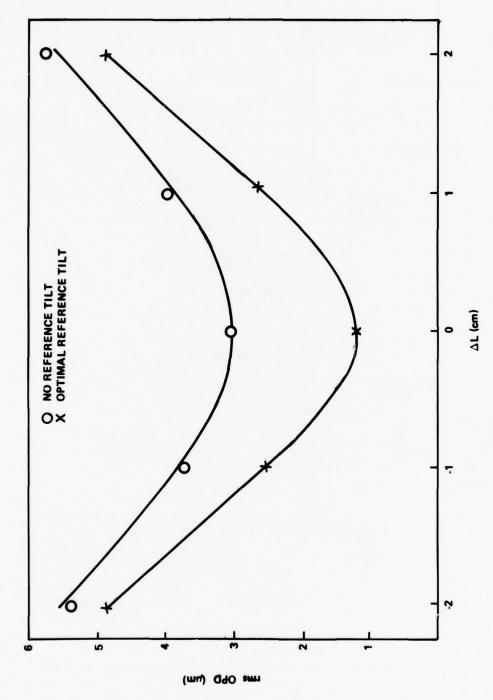
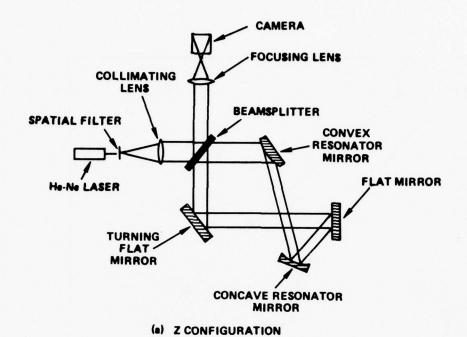


Figure 46. Predicted values (smooth curves) and calculated values of the root-mean-square OPD in microns as a function of ΔL , for Z configuration, θ_1 = 55°, $\Delta \theta_2$ = 0.



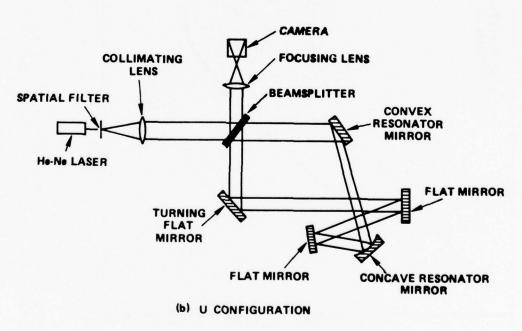


Figure 47. Experimental arrangement for obtaining interferograms.

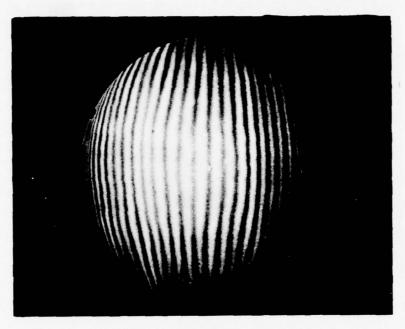


Figure 48. Variation of RBT, θ_1 = 45°, Z configuration.

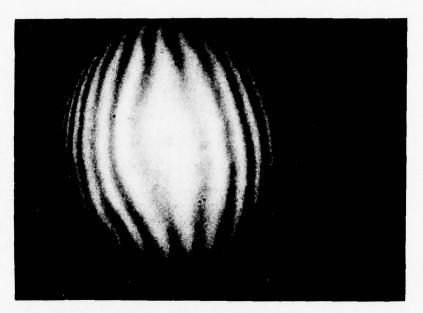


Figure 49(a). Variation of RBT, $\theta_1 = 45^{\circ}$, Z configuration.

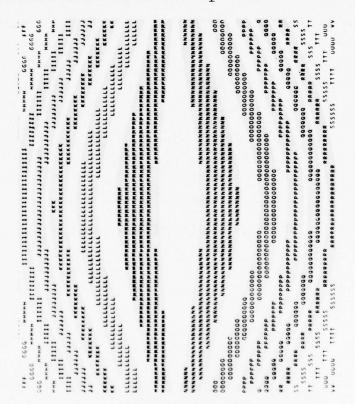


Figure 49(b). Theoretical OPD calculation, Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0.148 (-0.370).

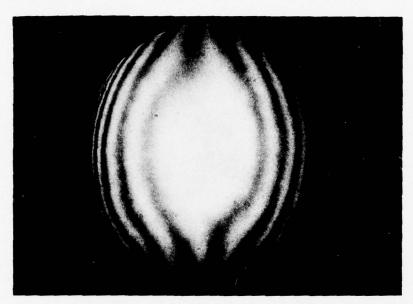


Figure 50(a). Variation of RBT, θ_1 = 45°, Z configuration.



Figure 50(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.074 (-0.370).

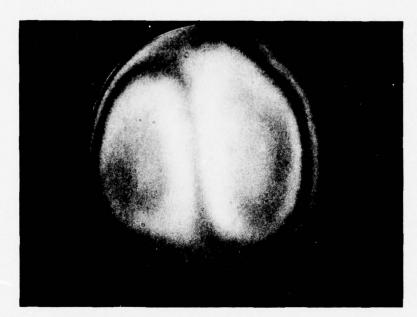


Figure 51(a). Variation of RBT, θ_1 = 45°, Z configuration.

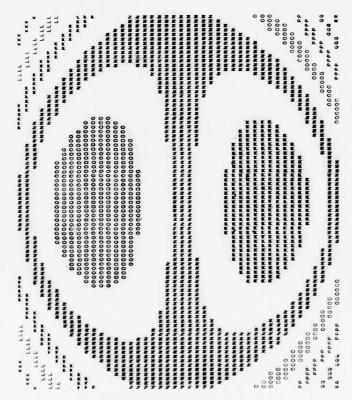


Figure 51(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.296 (-0.370).

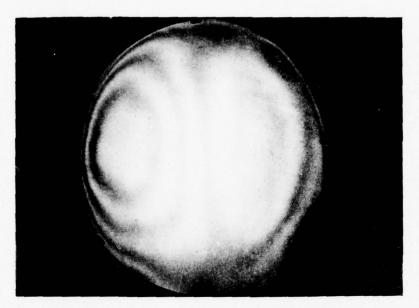


Figure 52(a). Variation of RBT, θ_1 = 45°, Z configuration.

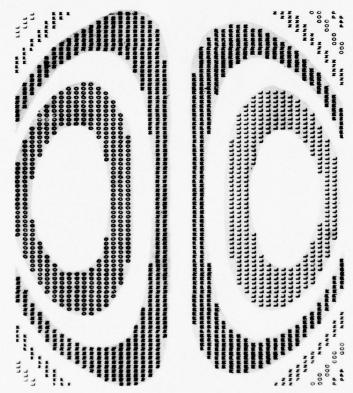


Figure 52(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.444 (-0.370).

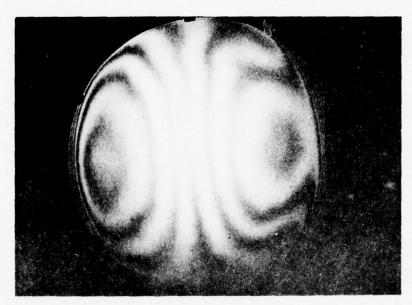


Figure 53(a). Variation of RBT, θ_1 = 45°, Z configuration.

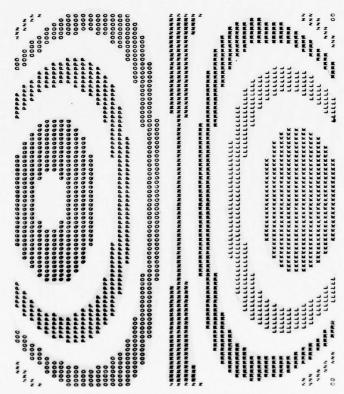


Figure 53(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = -0.592 (0.370).

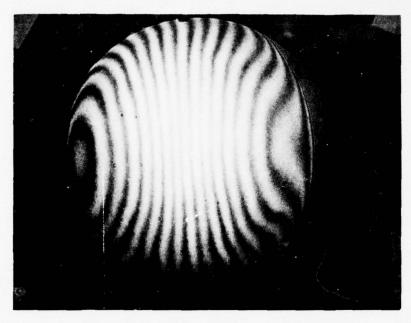


Figure 54(a). Variation in RBT, $\theta_1 = 45^{\circ}$, Z configuration.

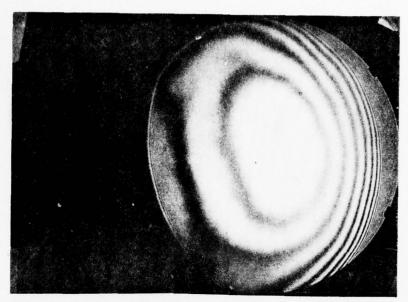


Figure 55(a). Misalignment in L, ΔL = 1 cm, θ_1 = 45°, Z configuration.

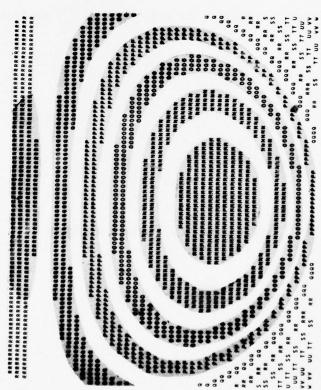


Figure 55(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0 (-0.361), L = 1.0 cm.

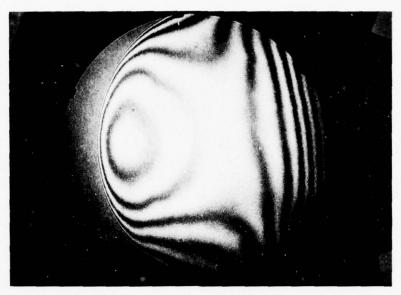
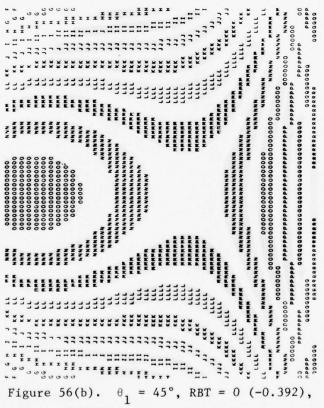


Figure 56(a). Misalignment in θ_2 , $\Delta\theta_2$ = 7 mrad, θ_1 = 45°, Z configuration.



 $\Delta\theta_2 = 0.007 \text{ rad}$, Z configuration.



Figure 57(a). Misalignment in θ_2 + $\Delta\theta_2$ = -7 mrad, θ_1 = 45°, Z configuration.

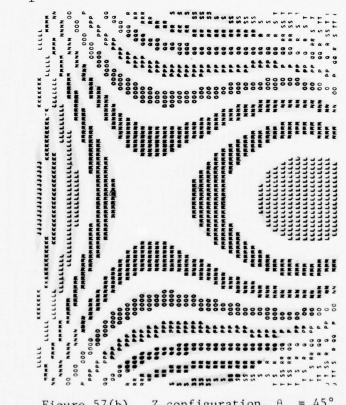


Figure 57(b). Z configuration, $\theta_1 = 45^{\circ}$, RBT = 0 (-0.348), $\Delta\theta_2 = -0.007$ rad.

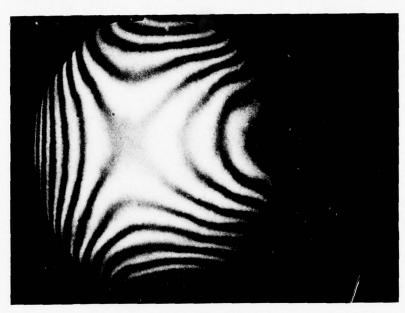


Figure 58. Misalignment in θ_2 , $\Delta\theta_2$ = 14 mrad, θ_1 = 45°, Z configuration.

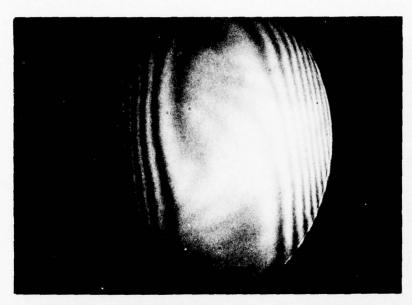
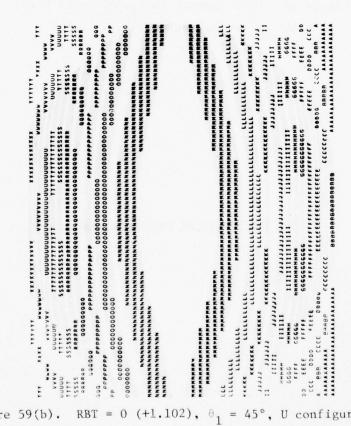


Figure 59(a). Variation of RBT, $\theta_1 = 45^{\circ}$, U configuration.



RBT = 0 (+1.102), θ_1 = 45°, U configuration. Figure 59(b).

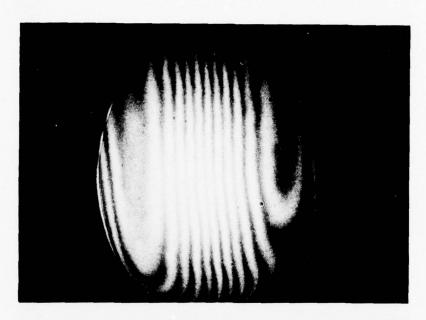


Figure 60(a). Variation of RBT, $\theta_1 = 45^{\circ}$, U configuration.

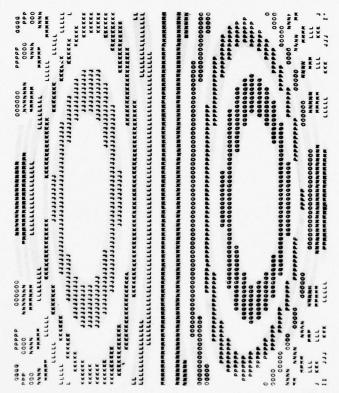


Figure 60(b). RBT = 1.102 (1.102), θ_1 = 45°, U configuration.

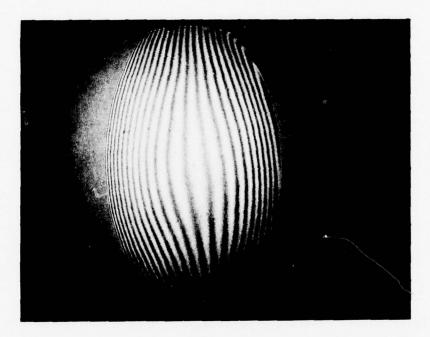


Figure 61. Variation of RBT, $\theta_1 = 70^{\circ}$, Z configuration.

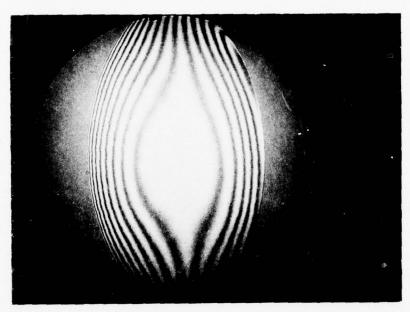


Figure 62(a). Variation of RBT, $\theta_1 = 70^{\circ}$, Z configuration.

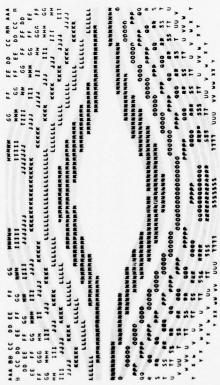


Figure 62(b). RBT = 0 (-1.997), $\theta_1 = 70^{\circ}$, Z configuration.



Figure 63(a). Variation of RBT, $\theta_1 = 70^{\circ}$, Z configuration.

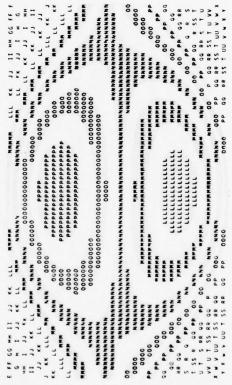


Figure 63(b). RBT = -0.799 (-1.997), $\theta_1 = 70^{\circ}$, Z configuration.

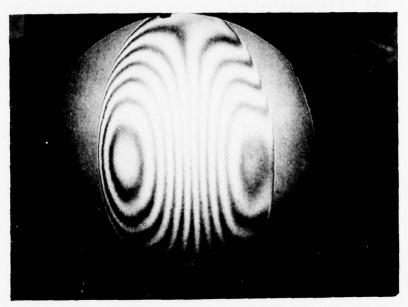


Figure 64. Variation of RBT, θ_1 = 70°, Z configuration.

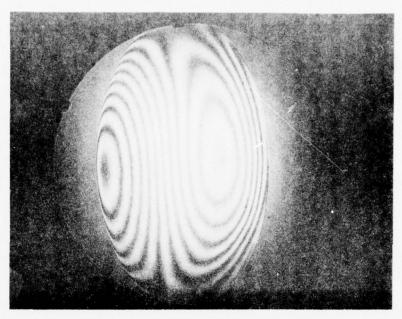


Figure 65. Misalignment in L, ΔL = 2 cm, θ_1 = 70°, Z configuration.

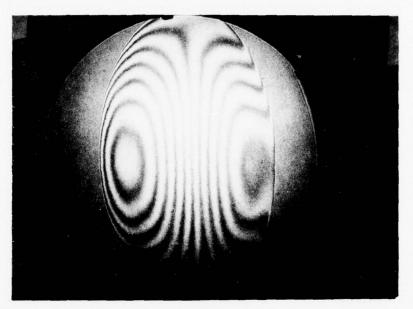


Figure 64. Variation of RBT, θ_1 = 70°, Z configuration.

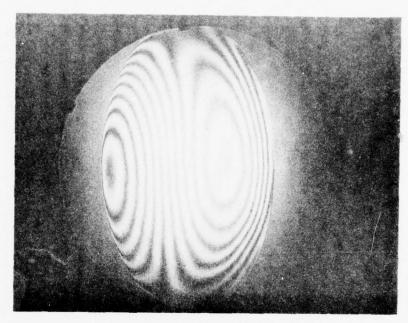


Figure 65. Misalignment in L, $\Delta L = 2$ cm, $\theta_1 = 70^{\circ}$, Z configuration.

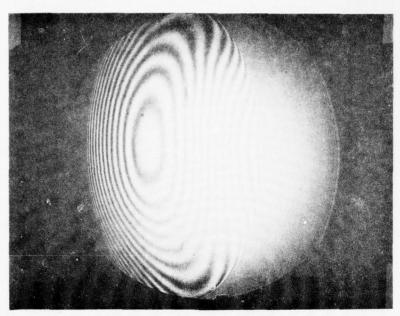
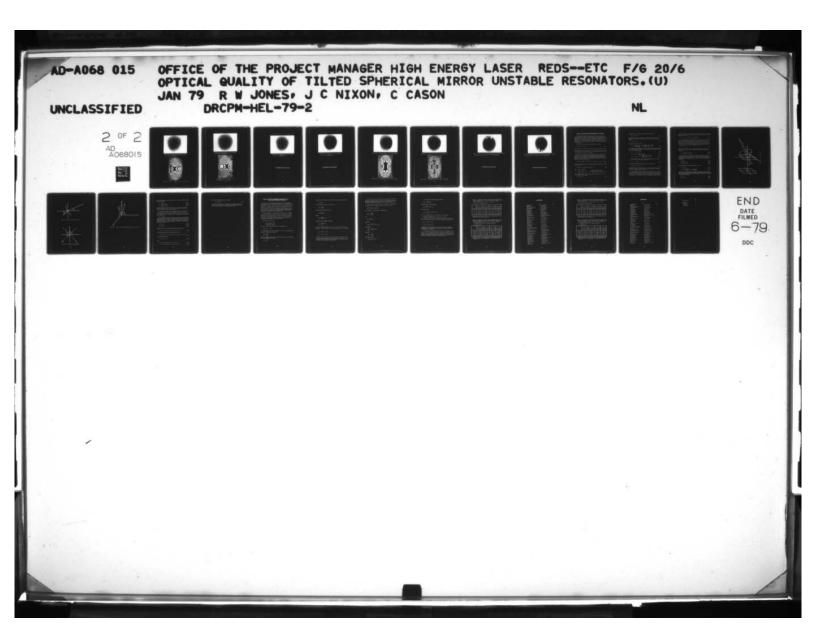


Figure 66. Misalignment in L, $\Delta L = -2$ cm, $\theta_1 = 70^{\circ}$, Z configuration.



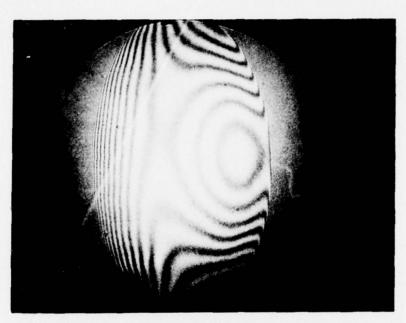


Figure 67(a). Misalignment of θ_2 , $\Delta\theta_2 = -7$ mrad, $\theta_1 = 70^\circ$, Z configuration.

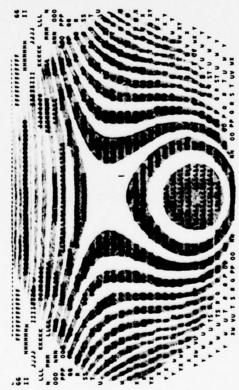


Figure 67(b). RBT = 0 (-1.837), $\theta_1 = 70^{\circ}$, $\Delta\theta_2 = -7$ mrad.

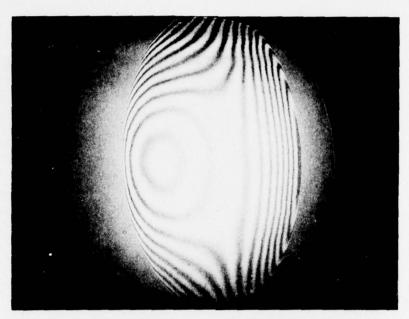


Figure 68(a). Misalignment of θ_2 , $\Delta\theta_2$ = 7 mrad, θ_1 = 70°, Z configuration.



Figure 68(b). RBT = 0 (-2.166), θ_1 = 70°, Z configuration, $\Delta\theta_2$ = 7 mrad.

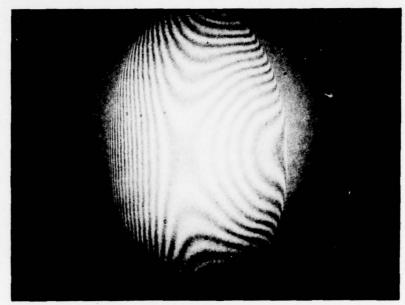


Figure 69. Misalignment in θ_2 , $\Delta\theta_2 = -14$ mrad, $\theta_1 = 70^\circ$, Z configuration.

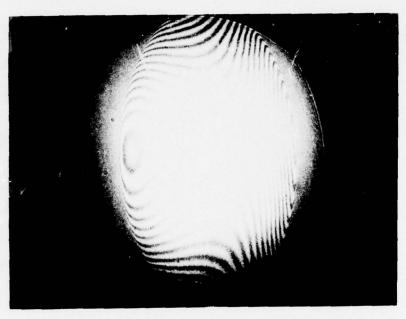


Figure 70. Misalignment in θ_2 , $\Delta\theta_2$ = 14 mrad, θ_1 = 70°, Z configuration.

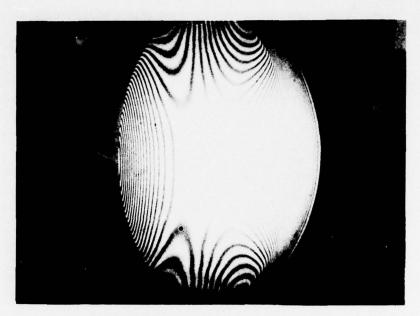


Figure 71(a). Variation of RBT, θ_1 = 70°, U configuration.

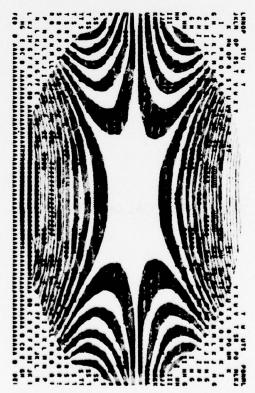


Figure 71(b). U configuration, θ_1 = 70°, RBT = 0 (3.698).

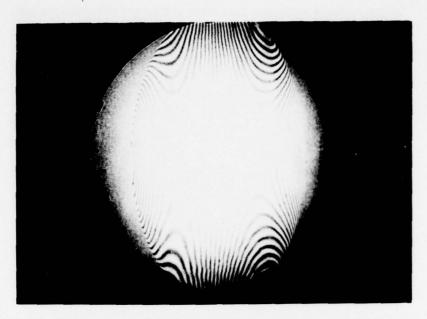


Figure 72(a). Variation of RBT, θ_1 = 70°, U configuration.

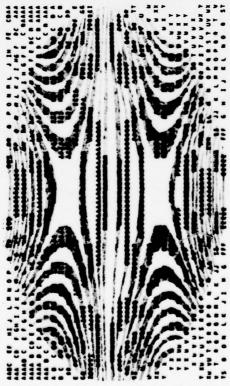


Figure 72(b). U configuration, $\theta_1 = 70^{\circ}$, RBT = 1.48 (3.698).

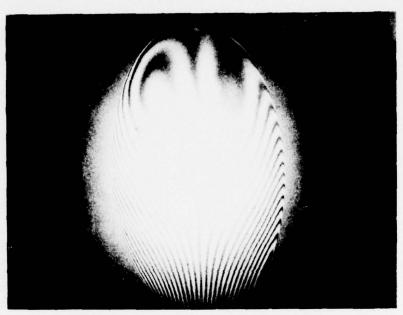


Figure 73. Tilt in θ_2 in a plane orthogonal to the plane of rotation of θ_1 and θ_2 , $\Delta\theta_2'$ = 7 mrad, θ_1 = 70°, Z configuration.

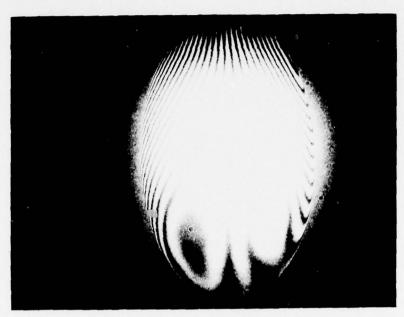


Figure 74. Tilt in θ_2 in a plane orthogonal to the plane of rotation of θ_1 and θ_2 , $\Delta\theta_2^{\bullet}$ = -7 mrad, θ_1 = 70°, Z configuration.

Appendix A. EQUATIONS FOR THREE-DIMENSIONAL RAY TRACING

The coordinate system used at a particular stage of ray-tracing calculations will ordinarily be chosen such that the central ray is along the positive z axis. Usually the origin of coordinates is at the intersection of the central ray with the spherical-mirror surface. The equations can be related to Figure A-1, which depicts the case of a convex mirror. Provision is made for the mirror to be tilted about the x-axis, i.e., in the y-z plane, by an angle T. The coordinate system is left-handed.

The basic ray-optics equation for reflection is simply

$$\bar{e}_r = \bar{e}_i - 2 \bar{n} \cos \theta,$$
 (A-1)

where \bar{e}_{i} and \bar{e}_{r} are unit vectors along the incident and reflected rays,

respectively, \bar{n} is a unit normal vector (pointed from the intersection point toward the mirror center), and θ is the angle between the incident (or reflected) ray and the mirror normal \bar{n} .

The mirror tilt angle T is taken as positive for counterclockwise rotation, i.e., from the positive z direction toward the positive y direction. The convention is adopted that the mirror curvature R is negative for convex mirrors. The coordinates of the mirror center are then 0, $-R \sin T$, $-R \cos T$; this is valid for either sign of R. The equation of the mirror surface is

$$\phi$$
 (x,y,z) = const = R² = x² + (y + R sin T)² + (z + R cos T)².

(A-2)

The unit normal vector can be determined by taking the gradient of this function, i.e.,

$$\bar{n} = \frac{1}{2R} \Delta \phi = \frac{x}{R}, \frac{y}{R} + \sin T, \frac{z}{R} + \cos T$$
 (A-3)

Now z can be eliminated:

$$\overline{n} = \left(\frac{x}{R}, \left(\frac{y}{R} + \sin T\right), \sqrt{1 - \left(\frac{x}{R}\right)^2}\right) = \left(\frac{y}{R} + \sin T\right)^2\right)$$
 (A-4)

The direction cosines of the incident ray are denoted by a, b, and c, i.e., giving vector equation:

$$\tilde{e}_{i} = (a,b,c) \tag{A-5}$$

and similarly, (using primes to denote the reflected ray),

$$\bar{e}_{r} = (a',b',c')$$
 (A-6)

The cosine of the angle θ between the incident ray and the surface normal is given by the dot product of the corresponding unit vectors, that is:

$$\cos \theta = \bar{e}_i \cdot \bar{n}$$
 (A-7)

This gives the explicit result:

$$\cos = \theta \ a \left(\frac{x}{R}\right) + b\left(\frac{y}{R}\right) + c \sqrt{1 - \left(\frac{x}{R}\right)^2 - \left(\frac{y}{R} + \sin T\right)^2} \qquad (A-8)$$

This equation can conveniently be used to determine the numerical value of θ . The direction cosines of the reflected ray can then be determined from the following equations:

$$a' = a - 2 \cos \theta \cdot \frac{x}{R} \qquad , \tag{A-9}$$

$$b' = b - 2 \cos \theta \cdot \left(\frac{y}{R} + \sin T\right) \qquad , \tag{A-10}$$

$$b' = b - 2 \cos \theta \cdot \left(\frac{y}{R} + \sin T\right),$$
 (A-10)
 $c' = c - 2 \cos \theta \cdot \sqrt{1 - \left(\frac{x}{R}\right)^2 - \left(\frac{y}{R} + \sin T\right)^2}$. (A-11)

For the special case of an incident ray parallel to the z-axis, i.e., for a = b = 0, the following is noted:

$$c' = c - 2 \cos^2 \theta \qquad . \tag{A-12}$$

The necessary relationship between the direction cosines

$$(a')^2 + (b')^2 + (c')^2 = 1$$
 (A-13)

is reserved here for a possible test, but is not used to determine the value of c', because an Equation (11-A) which determines the sign as well as the magnitude of c' is needed.

Equations (9-A) through (11-A) for direction cosines of reflected ray require knowledge not only of direction cosines of incident ray but also of the coordinates of the point of intersection of the incident ray with the mirror. In general, these must be determined from a separate calculation. For the special case of the incident ray parallel to the

z-axis, encountered in starting some ray-tracing problems, x and y will be given, and z can be determined from the equation obtained by solving Equation (A-2) for z:

$$z = -R \cos T - \sqrt{R^2 - x^2 - (y + R \sin T)^2}$$
 (A-14)

At various stages in the calculations, it will be desirable to make rotational coordinate transformation. In particular, such a rotation of coordinates will be made after each reflection from a spherical mirror. As indicated in Figure A-2, the direction of the central ray is changed such that the associated angle in the z-y plane is increased by π + 2 T, where T is the mirror tilt angle, taken as positive for counterclockwise rotations. This is denoted by \bullet , i.e.:

$$\Theta = \pi + 2 T \qquad . \tag{A-15}$$

With reference to Figure A-3, a rotational transformation from an unprimed to a primed coordinate system as shown has the transformation equations:

$$z' = z \cos \theta + y \sin \theta$$
 , (A-16)

$$y' = -z \sin \phi + y \cos \phi . \tag{A-17}$$

The effect of the coordinate rotation on direction cosines can be derived by reference to Figure A-4. The polar and azimuthal angles V and W define the direction of the ray vector E, which is alternatively defined by the direction cosines a, b, and c. Thus the following can be written:

$$a = \cos V$$
 , (A-18)

$$b = \sin V \sin W$$
 , (A-19)

$$c = \sin V \cos W$$
 . (A-20)

These equations can be readily solved for V and W:

$$V = \cos^{-1}(a)$$
 , (A-21)

$$W = \sin^{-1} \left(\frac{b}{\sin V} \right) = \cos^{-1} \left(\frac{c}{\sin V} \right) \qquad (A-22)$$

The effect of a rotation about the x-axis, measured as positive in the sense discussed previously is to reduce W algebraically by the magnitude of the rotation angle, while the polar angle V is unaffected. Thus, the following can be written:

$$V' = V \qquad (A-23)$$

$$W' = W - \Theta \qquad . \tag{A-24}$$

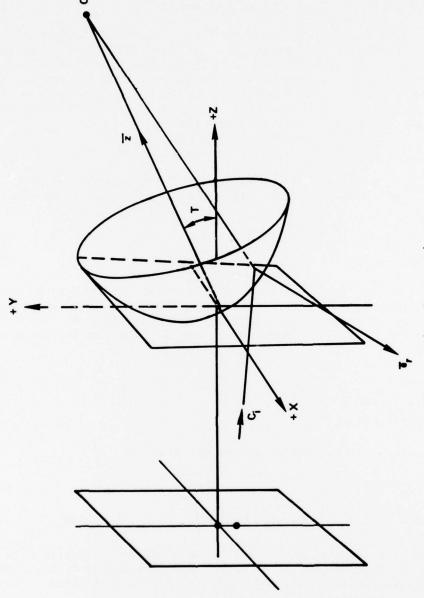


Figure A-1. Convex mirror.

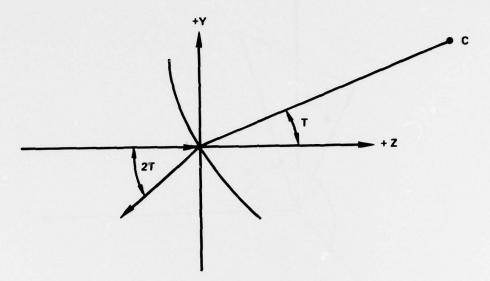


Figure A-2. Direction of the central ray.

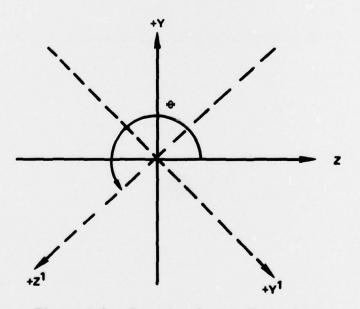


Figure A-3. Rotational transformation.

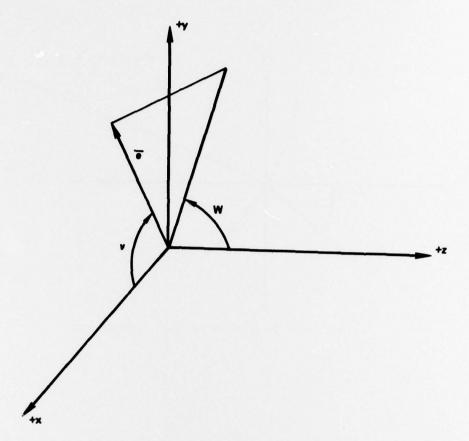


Figure A-4. Effect of coordinate rotation on direction cosines.

The direction cosines can then be written in the rotated frame in terms of the new angles:

$$a'' = \sin(V) = a$$
 , (A-25)

$$b'' = \sin(V) \sin(W') , \qquad (A-26)$$

$$c'' = \sin(V) \cos(W') \qquad . \tag{A-27}$$

Here double primes are used on the a, b, and c simply to distinguish from the equations relating to the change in direction cosines as a result of reflection from a spherical mirror.

For computer evaluation of W, the proper quadrant must be chosen. A suitable method is evaluating the magnitude of W from the second part of Equation (A-22) involving the \cos^{-1} function, but with the sign of W chosen to conform to the first part of Equation (A-22), involving the \sin^{-1} function.

After finding the direction cosines and coordinates at the mirror-intersection point, referred to a coordinate system with positive z-axis along central ray, the case that the next mirror is also a spherical mirror is considered. First the point of intersection of the ray with this mirror is found. For this purpose, the parametric equations with t are written for the ray as:

$$x' = x + a t , (A-28)$$

$$y' = y + b t , (A-29)$$

$$z' = z + c t$$
 . (A-30)

Equation (A-2) can be rewritten defining the mirror surface:

$$(x')^2 + (y' + R \sin T)^2 + (z' + R \cos T)^2 = R^2$$
 (A-31)

Substituting Equations (A-28) through (A-30) gives:

$$(x + at)^2 + (y + R \sin T + bt)^2 + (z + R \cos T + ct)^2 = R^2.$$
(A-32)

This can be expressed as:

$$t^2 + 2 B t + C = 0$$
 , (A-33)

where

$$B = ax + b(y + R \sin T) + c(z + R \cos T)$$
, (A-34)

$$C = x^2 + (y + R \sin T)^2 + (z + R \cos T)^2 - R^2$$
 (A-35)

The solution to Equation (A-33) is simply:

$$t = -B + \sqrt{B^2} = C$$
 (A-37)

The choice of sign in front of the square root should be such as to obtain a positive solution. It should be the smaller in magnitude of the two in the event that there are two positive roots.

Appendix B. EFFECTS OF INCREMENTS TO MIRROR SPACING L AND TO CONCAVE-MIRROR TILT ANGLE θ_2

By the nature of the concept, there will be no net focusing or defocusing, i.e., no second-power term in x or y in the equation for a constant-phase surface, in the output when both L and θ_2 are set precisely at their nominal values. This fact is of considerable practical importance. But because there may be small departures of ΔL and $\Delta\theta_2$ from their nominal values, it is appropriate to investigate the predicted effects (i.e., predicted in a fairly simple closed-form analysis as given in this appendix) of such departures and to compare these predictions to results of detailed calculations.

First, increments ΔL are considered. The effective focal lengths of the mirrors in the x-z plane are denoted by F_{1x} and F_{2x} . Similar notation will be employed for the y-z plane; differences in the two cases arise only from the presence of $\cos\theta_2$ or $\sec\theta_2$. F_{Tx} denotes the effective focal length in the x-z plane of the output beam. The following lens-type equation can then be written:

$$\frac{1}{F_{Tx}} = \frac{1}{F_{1x} - L - \Delta L} + \frac{1}{F_{2x}}$$

$$= \frac{F_{2x} + (F_{1x} - L - \Delta L)}{(F_{1x} - L - \Delta L)F_{2x}}$$

But L has a value such that the output is collimated, i.e.,

$$F_{2x} + F_{1x} - L = 0$$
.

It is here understood that F_{1x} is negative. Then, to a good approximation, the following can be written:

$$\frac{1}{F_{Tx}} = \frac{\Delta L}{(F_{2x})^2}$$

Now the incremental optical path length for the case of a wave focusing with focal length $\boldsymbol{F}_{T_\mathbf{X}}$ is simply

$$z = c_{20} x^2$$

Similarly, for focusing in the y-z plane, the following is obtained:

$$z = C_{02} y^2$$
.

The corresponding value of C_{20} is given by

$$C_{20} = -\frac{1}{2F_{Tx}}$$

The specific expression for F_{2x} is

$$F_{2x} = \frac{R_2}{2} \sec \theta_2 \qquad ;$$

hence,

$$C_{20} = -\frac{2\Delta L}{R_2^2} \cos^2 \theta_2 \qquad .$$

Similarly, the following is obtained:

$$C_{02} = -\frac{2\Delta L}{R_2} \sec^2 \theta_2 \qquad .$$

A numerical example with R_2 = 675 cm, θ_1 = 55°, θ_2 = 38.76° has been considered. The predictions of the preceding equations for this example are

$$c_{20} = -0.267 \times 10^{-5} \Delta L$$

$$c_{02} = -0.722 \times 10^{-5} \Delta L$$

The values of $\rm C_{20}$ and $\rm C_{02}$ have also been determined by simple function-fitting to results of numerical OPD calculations. A comparison of these latter calculated results with the predicted results derived is given in Table B-1. The agreement is satisfactory.

It should be noted that the signs of $\rm C_{20}$ and $\rm C_{02}$ are the same for increments in mirror-spacing L. That is to say, the net focusing or defocusing (converging or diverging) effect is qualitatively the same (though quantitatively different) in the two transverse planes.

Next, the effect of an incremental tilt angle $\Delta\theta_2$ is considered. The equation for focal length of output in x-z plane is now

$$\frac{1}{F_{Tx}} = \frac{1}{F_{1x} - L} + \frac{1}{F_{2x} + \Delta F_{2x}}$$

which reduces to a high degree of approximation to

$$\frac{1}{F_{Tx}} = -\frac{\Delta^{F_{2x}}}{(F_{2x})^{2}}$$

but,

$$F_{2x} = \frac{R_2}{2} \sec \theta_2$$

and hence

$$\Delta F_{2x} = \frac{R_2}{2} \sec \theta_2 \tan \theta_2 \Delta \theta_2$$

This leads to

$$\frac{1}{\mathbf{F}_{\mathbf{T}\mathbf{v}}} = -\frac{2}{\mathbf{R}_2} \sin \theta_2 \Delta \theta_2$$

but again,

$$c_{20} = -\frac{1}{2F_{Tx}}.$$

This finally gives

$$C_{20} = \frac{1}{R_2} \sin \theta_2 \Delta \theta_2$$

For the yz plane, the following is obtained:

$$F_{2y} = -\frac{R_2}{2} \cos \theta_2 \qquad .$$

The following is readily obtained:

$$F_{2y} = \frac{R_2}{2} (-\sin \theta_2) \Delta \theta_2 .$$

This finally gives

$$C_{02} = -\frac{1}{R_2} \sin \theta_2 \sec^2 (\theta_2) \Delta \theta_2$$

In the preceding equations $\Delta\theta_2$ is assumed to be in radians.

A numerical example with R $_1$ = -290 cm, R $_2$ = 675 cm, θ_1 = 0.95993 rad (55°), and θ_2 = 0.67647 rad (38.76°) has been considered. The predicted values of the quadratic parameters C $_{20}$ and C $_{02}$ are

$$c_{20} = 0.927 \times 10^{-3} \Delta\theta_2$$

$$c_{02} = -1.525 \times 10^{-3} \Delta\theta_2$$

A comparison of values predicted in this way with values obtained by function-fitting to numerically calculated OPDs is given in Table B-2. The agreement is satisfactory.

 c_{20} and c_{02} have opposite signs for the case of increments in tilt angle θ_2 . This is readily understood by noting that the effective focal lengths in the two transverse planes are changed in opposite directions by such an incremental tilt angle. This behavior is in contrast to the behavior with regard to increments in mirror spacing.

TABLE B-1. COMPARISON OF PREDICTED AND CALCULATED VALUES OF BEAM CURVATURE PARAMETERS C_{20} AND C_{02} RESULTING FROM INCREMENTS ΔL IN MIRROR SEPARATION. (R₁ = -290 cm, R₂ = 675 cm, θ_1 = 55°, θ_2 = 38.76°, L = 180.01005 cm)*

	^C 20		c ₂₀	
L (cm)	Predicted	Calculated	Predicted	Calculated
+1.0	-0.267E-5	-0.268E-5	-0.722E-5	-0.728E-5
-1.0	+0.267E-5	+0.266E-5	+0.722E-5	+0.716E-5
+2.0	-0.534E-5	-0.536E-5	-1.444E-5	-1.457E-5
-2.0	+0.534E-5	+0.531E-5	+1.444E-5	+1.430E-5

^{*}Predicted values are the same for Z and U configurations; calculated values are for Z configurations.

TABLE B-2. COMPARISON OF PREDICTED AND CALCULATED VALUES OF BEAM CURVATURE PARAMETERS C_{20} AND C_{02} RESULTING FROM INCREMENTS $\Delta\theta_2$ IN CONCAVE-MIRROR TILT ANGLE. (R₁ = -290 cm, R₂ = 675 cm, θ_1 = 0.95993 rad (55°), θ_2 = 0.67647 rad (38.76°), L = 180.01005 cm)*

	c ₂₀		c ₀₂	
θ2	Predicted	Calculated	Predicted	Calculated
+0.0035	+0.324E-5	+0.325E-5	-0.534E-5	-0.540E-5
-0.0035	-0.324E-5	-0.324E-5	+0.534E-5	+0.528E-5
+0.0070	+0.648E-5	+0.652E-5	-1.068E-5	-0.082E-5
-0.0070	-0.648E-5	-0.646E-5	+1.068E-5	+1.054E-5

^{*}Predicted values are the same for Z and U configurations; calculated values are for Z configurations. Note that 0.0035 rad 0.2°.

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TABLE B-1. COMPARISON OF PREDICTED AND CALCULATED VALUES OF BEAM CURVATURE PARAMETERS C AND C RESULTING FROM INCREMENTS ΔL IN MIRROR SEPARATION. (R = -290 cm, R = 675 cm, θ_1 = 55°, θ_2 = 38.76°, L = 180.01005 cm)*

	^C 20		c ₂₀	
L (cm)	Predicted	Calculated	Predicted	Calculated
+1.0	-0.267E-5	-0.268E-5	-0.722E-5	-0.728E-5
-1.0	+0.267E-5	+0.266E-5	+0.722E-5	+0.716E-5
+2.0	-0.534E-5	-0.536E-5	-1.444E-5	-1.457E-5
-2.0	+0.534E-5	+0.531E-5	+1.444E-5	+1.430E-5

^{*}Predicted values are the same for Z and U configurations; calculated values are for Z configurations.

TABLE B-2. COMPARISON OF PREDICTED AND CALCULATED VALUES OF BEAM CURVATURE PARAMETERS C_{20} AND C_{02} RESULTING FROM INCREMENTS $\Delta\theta_2$ IN CONCAVE-MIRROR TILT ANGLE. (R₁ = -290 cm, R₂ = 675 cm, θ_1 = 0.95993 rad (55°), θ_2 = 0.67647 rad (38.76°), L = 180.01005 cm)*

	c ₂₀		C ₀₂	
θ2	Predicted	Calculated	Predicted	Calculated
+0.0035	+0.324E-5	+0.325E-5	-0.534E-5	-0.540E-5
-0.0035	-0.324E-5	-0.324E-5	+0.534E-5	+0.528E-5
+0.0070	+0.648E-5	+0.652E-5	-1.068E-5	-0.082E-5
-0.0070	-0.648E-5	-0.646E-5	+1.068E-5	+1.054E-5

^{*}Predicted values are the same for Z and U configurations; calculated values are for Z configurations. Note that 0.0035 rad 0.2°.

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